R-798

VOLUME IV
MULTIPLE IMU SYSTEM TEST PLAN

by

Martin Landey
Kenneth T. Vincent, Jr.
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October 1974

The Charles Stark Draper Laboratory, Inc.
Cambridge, Massachusetts 02139

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Approved: N. E. Sears Date: 11-22-74

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ABSTRACT

Operating procedures for this redundant system are described. A test plan is developed with two objectives. First, performance of the hardware and software delivered is demonstrated. Second, applicability of multiple IMU systems to the space shuttle mission is shown through detailed experiments with FDI algorithms and other multiple IMU software: gyrocompassing, calibration, and navigation. Gimbal flip is examined in light of its possible detrimental effects on FDI and navigation.

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1.0 INTRODUCTION

This document forms part of the final report on the Space Shuttle Avionics Multiple IMU System, NASA/MSFC Contract NAS8-27624.

The contract was originally awarded to the Charles Stark Draper Laboratory on July 7, 1971. The initial twelve month effort was devoted to the study and definition of failure detection and isolation (FDI) requirements for a multiple gimbaled system. It also addressed prelaunch requirements for calibration, ground alignment and gyrocompassing as well as an inertial navigator. Under this task, a preliminary test plan was formulated around the demonstration of FDI development using three redundant KT-70 IMUs and a single 4π-CP2 computer. An interim report covering this work phase (R-733, Space Shuttle Avionics A Redundant IMU On-Board Checkout and Redundancy Management System) was published in September, 1972.

This contract was amended in June, 1972, to add several additional tasks. Detailed electronic integration design of all system units was to be accomplished. These interface units would be assembled and their designs verified. An integrated, redundant IMU system would be demonstrated and delivered to NASA/MSFC. Software for this system was also specified. Deliverable software included ground alignment and gyrocompassing, an inertial navigator, and a full range of FDI programs (Tape 1). A multi IMU calibration program was also required (Tape 2).

This final report is organized into four volumes which will present in detail all activity under the extension of the original contract which was approved on 3 August, 1972. This extension provides development of both hardware interfaces and software coding for a laboratory demonstration of this redundant IMU system based upon three KT-70 IMUs and a single 4π-CP2 computer.

The four volumes describe analytical and developmental activities, hardware design, software design, and a system test plan. Each volume is described briefly below.

Volume I–Multiple IMU System Development

A review of the contract is presented. Analytical work and digital simulations defining system requirements are fully described. Failure detection and isolation algorithms are derived.

Volume II–Multiple IMU System Hardware Interface Design

Design of each system component is described. Emphasis is placed on functional requirements unique in this system, including data bus communication, data bus transmitters and receivers, and ternary-to-binary torquing decision logic. System mechanization drawings are presented.

Volume III–Multiple IMU System Software Design and Coding

Design of system software is explained; both individual routines and their interplay are described. Executive routines, ground alignment, gyrocompassing, navigation and calibration routines are presented and described using flowcharts. Failure detection and isolation algorithms and system reconfiguration procedures are also presented and described with flowcharts.

Volume IV–Multiple IMU System Test Plan

Operating procedures for this redundant system are described. A test plan is developed with two objectives. First, performance of the hardware and software delivered is demonstrated. Second, applicability of multiple IMU systems to the space shuttle mission is shown through detailed experiments with FDI algorithms and other multiple IMU software: gyrocompassing, calibration, and navigation. Gimbal flip is examined in light of its possible detrimental effects on FDI and navigation.

1.1 Introduction to Volume IV

This test plan presented is designed, initially, to verify the complete configuration and all individual subroutines to ensure system operation as a multiple IMU test bed and, secondly, to evaluate the system and its many subroutines for compatibility with the space shuttle requirements of prelaunch, boost, on-orbit, entry, TAEM (terminal area energy management) and the Autoland segments of flight as they are presently defined.

The present test plan is of necessity preliminary and is being reordered and expanded as it is being carried out to include current priorities, more detailed evaluations in areas where the present capabilities are not clearly demonstrated, and changed to permit new ideas and techniques to be evaluated for application in the shuttle mission. It is our ultimate hope that this multiple system test tool will have sufficient interest and backing of Shuttle design and development agencies to permit active use as a prototype in hardware and software concept feasibility verification as well as to provide a practical gauge of software memory and real-time timing requirements.

The present test plan is written specifically for the test engineer and provides descriptions of programs which are required, how to bring the configuration to the point of initialization of each test requested and what data is required for test completion including required signals, update rates and tolerances.

1.2 Proposed Test Schedule

The tests proposed in this report are expected to require eight months to complete. A schedule for this work is presented as Figure 1-1, Proposed Test Program Schedule. The priorities of testing presented are the result of joint agreement with both NASA/MSFC and NASA/JSC.

Integration and verification of the multiple IMU system is projected to require about four weeks. It should be emphasized that assembly at NASA/MSFC will mark the first time that more than one IMU is on line, and, therefore, will first permit evaluation of system software with multiple inputs. (Single IMU verification was accomplished at CSDL before system delivery.) In addition, the 4π-CP2/HP2116B interface (the digital link to NASA/MSFC's SSCMS) must be verified in place.

FDI algorithm evaluation is given first priority in this test plan. This evaluation is expected to require three to four months. Velocity information-based and attitude information-based algorithms will be demonstrated for both three and two IMU systems. Detailed studies of the effect of inter-IMU misalignments are suggested, as is experimentation with thresholds. This study will be supplemented by an available computer simulation so that the results can be expanded and unified without requiring the entire evaluation be done in hardware.

Gyrocompassing studies are planned in a two week interval aimed at evaluating multiple system performance attained with simultaneous gyrocompassing. Examination of gimbal flip and its effect on both navigation and FDI will be carried out over a three week period. Degradation of inertial reference and data loss during flip are to be studied. The studies will be aimed at the quality of attitude information around and in the flip region so that an operational philosophy can be developed both by judging attitude quality and the implications of interface timing (attitude staleness and skewness) problems.

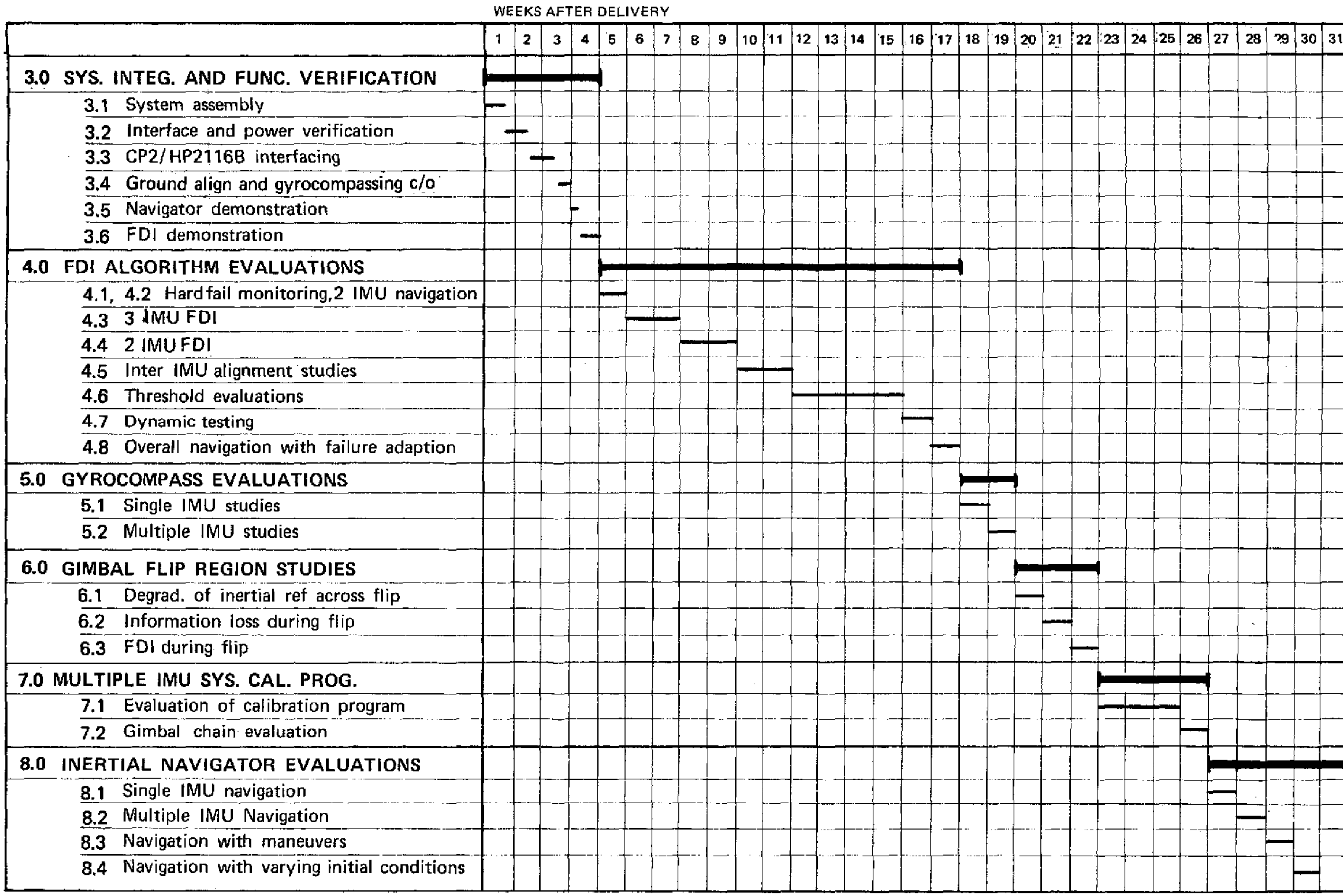


Figure 1-1. Proposed Test Program Schedule.

The present calibration program shall be examined giving particular attention to the g-sensitive gyroscope errors. Using these results directly in the multiple system compensation models implemented will give a good indication of the calibration model completeness and stability within the laboratory environment as evidenced, in part, by the system's ability to perform accurate inertial navigation.

All of the proposed tests, especially FDI work, will use an inertial navigator as an evaluation tool. The final test sequence will evaluate the multiple system overall capability in performance using the inertial navigator under various initial conditions and in special environments.

2.0 EQUIPMENT AND FACILITIES

This test plan is designed to prove out concepts associated with redundant inertial measurement units employed collectively, as is planned for use in the space shuttle vehicle. A detailed description of the system hardware appears as Volume II of this report, Multiple IMU System Hardware Interface Design, August, 1974. An overview of this system will now be presented.

The work described in this report is being carried out at NASA/MSFC, using the Strapdown System Control and Monitoring Station (SSCMS) and ancillary equipment which is also described below.

2.1 Multiple IMU System Hardware

The system under test may be described as a redundant inertial system whose three IMUs are linked to a single flight computer by a simple, serial transmission data bus. Three aircraft Kearfott KT-70 (AN/ASN-90) IMUs are employed, each with its own Adaptor Power Supply (APS). An IBM 4π-CP2 computer, with auxiliary memory, tape reader and punch, and a typewriter, forms the computer complement for this equipment.

As shown in Figure 2-1, Multiple IMU System Interconnection Diagram, each IMU/APS pair is mated with an Interface Unit (IU) which encodes and decodes communication with the 4π-CP2 (via the data bus), and distributes power to the APS. The IU includes a synchro-to-digital (S/D) converter for each of the three synchros in the IMU, the logic necessary to command gyro dithering by binary torquing, and system monitoring capability.

The data bus consists of four twisted shielded pairs, each assigned specifically to one of these functions: transmit data (4π-CP2 to IMU), transmit clock, read data (IMU to 4π-CP2), read clock. Bus receivers and transmitters operate at 10 MHz, using bipolar alternate-mark-inversion code.

A Processor Interface Unit (PIU) serves to encode and decode data bus transmissions for the 4π-CP2. In addition, it includes a digital interface to NASA/MSFC's SSCMS. This additional digital interface permits use of mass data storage, displays and line printers associated with the SSCMS as part of multiple IMU system's computer complex.

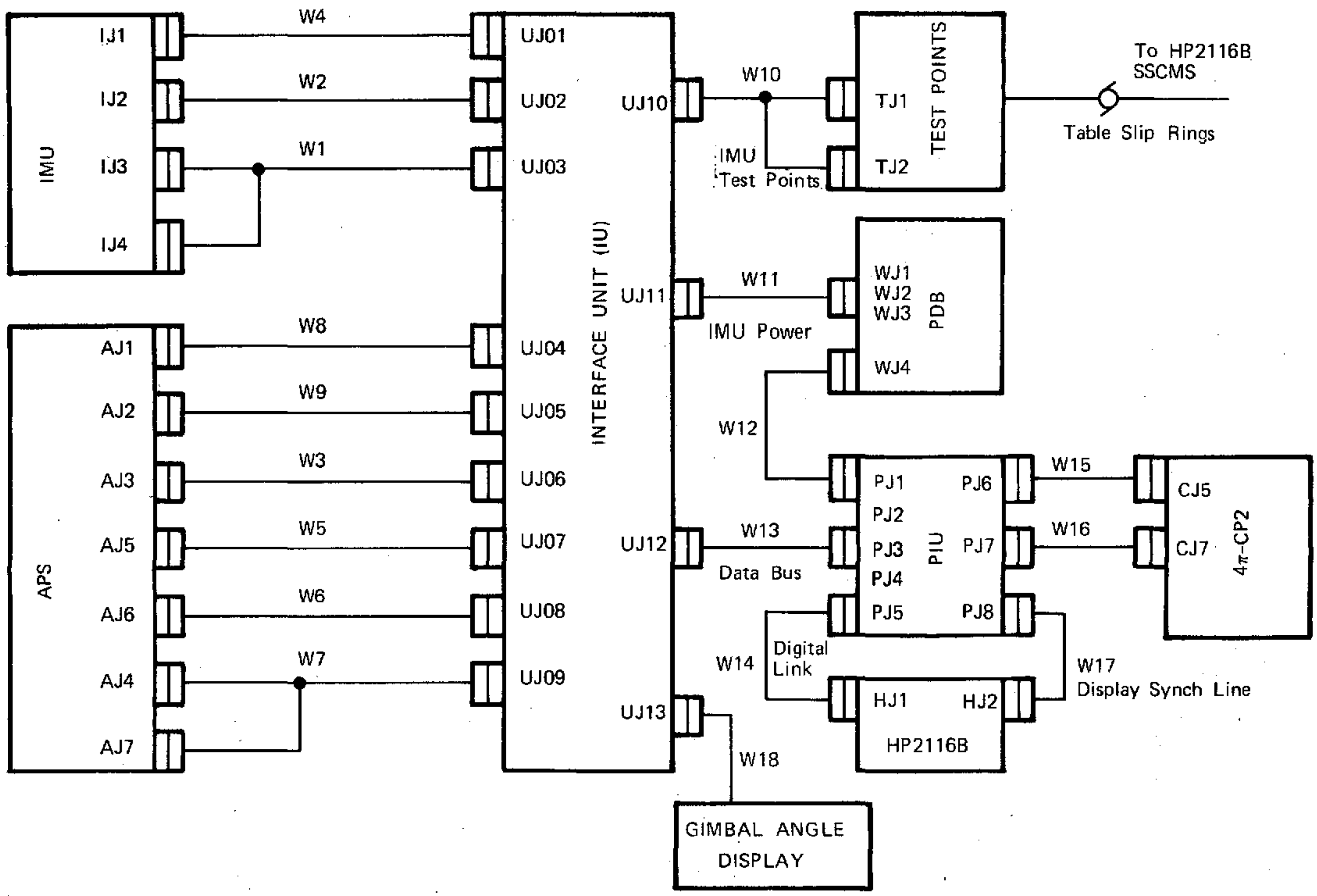


Figure 2-1. System Interconnect Diagram (One IMU Shown).

The multiple IMU system also includes a Power Distribution Panel (PDB), a digital gimbal angle display and cabling. System assembly and checkout procedures, and system acceptance tests are more fully described in a CSDL memorandum, MULTIPLE KT-70 SYSTEM Assembly and Checkout Procedure and Acceptance Tests, Avionics Memo #74-4, and will not be fully documented as part of this report.

2.2 Definition of System Polarities

In the multiple IMU system, all calculations including inertial instrument calibration and compensation are referenced to a stable member fixed, right-handed computational frame. A separate computational frame is defined for each IMU, although it is assumed that gyrocompassing of colinear platforms coaligns it with the navigation frame. Within each IMU, the accelerometer input axes (IAs) and gyro input axes form two distinct left-handed triads, each of which is also stable member fixed.

Digital gyro torquing and analog gyro slew commands are calculated in the computational frame; the executive alters these commands to reflect physical orientation of the instruments, where necessary, prior to transmitting them to the IU.

System polarities are defined to meet one basic condition: with gimbal angles (0, 0, 0) so that the computational frame is coincident with the triad of gimbal axes, a physical rotation of the platform about a positive computational axis yields positive rotation about the associated gimbal axis, and is displayed as an increasing angle as indicated by the S/D convertors.

2.2.1 Triad Definitions

The computational frame is a mathematical abstraction of the stable member frame. It is a right-handed triad (X_c, Y_c, Z_c) which may be thought of, in a caged, error free gimbal set as coincident with the roll, pitch and yaw axes, respectively. The alignment and gyrocompassing programs for this system align the computational frame such that

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} = \begin{bmatrix} \text{North} \\ \text{West} \\ \text{Up} \end{bmatrix}$$

With the gimbal case level and the fore axis pointing north, this orientation should yield (0, 0, 0) gimbal angles. These two conditions shall define the standard orientation of the platform, as shown in Figure 2-2a, Definition of Standard Orientation.

Inertial instrument input axis triads are determined by Kearfott hardware. In each case (gyro and accelerometer), one IA is anti-parallel to the computational axis it is associated with. Thus, the gyro IAs are as shown in Figure 2-2b, Gyro IA Triad Physical Placement, forming a left handed triad. Torquing commands are generated with respect to the computational frame. The system executive reverses the sign of the X gyro channel command before the data is transmitted. Positive GYPTO commands result in positive platform rotation relative to the vehicle or test table about the instantaneous computational axis. Positive analog slew commands result in positive platform rotation (where Slew Sense=0 is termed positive (see Table 3-1)). That is, a "+1" in GYPTO and a"+1" in Slew Sense have opposite physical realizations.

Accelerometer input axes also form a left-handed triad, as in Figure 2-2c, Accelerometer IA Triad Physical Placement. Accelerometer output (CAPRI) data for the Y channel is complemented by the system executive before processing.

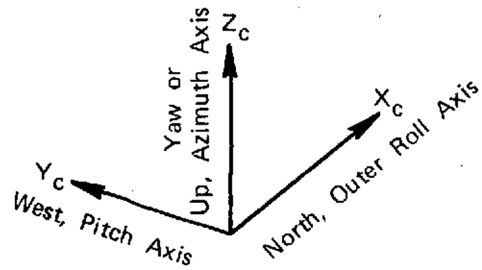
2.2.2 Gimbal Angle Definitions

With gimbal angles (0, 0, 0), the computational frame is nominally coincident with gimbal axes:

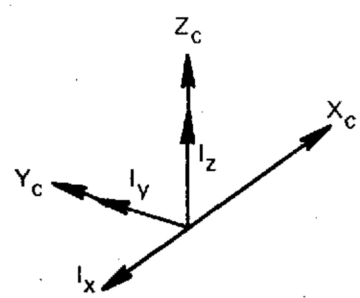
$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} = \begin{bmatrix} \text{Roll} \\ \text{Pitch} \\ \text{Yaw} \end{bmatrix}$$

With the gimbals caged, a positive rotation of the platform about the X_c (or $-I_x$) axis yields an increasing roll angle. This is equivalent to gimbal motion resulting from a "right wing up" maneuver. A positive rotation of the platform about Y_c (or $+I_y$) yields an increasing pitch angle, equivalent to a "nose-up" maneuver. Positive rotation about Z_c (or $+I_z$) yields an increasing azimuth angle as would a "right wing back" maneuver.

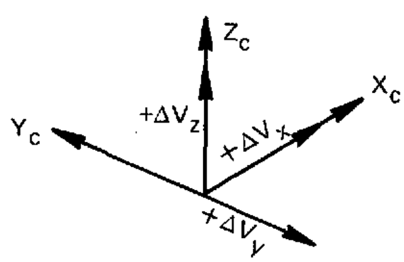
A mechanical rotation of the IMU is sensed by the gyros. Platform orientation is maintained by counter rotation space stabilization via the servo loop. Thus, a vehicle rotation in the positive yaw sense (See Figure 2-2d) is detected as a negative



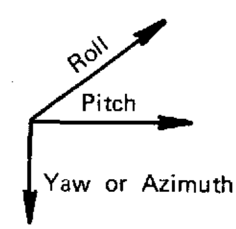
a) Definition of Standard Orientation



b) Gyro IA Triad Physical Placement



c) Accelerometer IA Triad Physical Placement



d) Nominal Vehicle Axes

Figure 2-2. Definition of System Triads.

rotation about the Z_c axis. The azimuth servo loop acts to negate that rotation by torquing the gimbals about the positive I_z axis.

2.2.3 Sense of Inertial Component Error Parameters

Definition of error parameter senses can be completely arbitrary providing that there is agreement between calibration and compensation routines. In this system, one complication arises. One gyro axis (and similarly, one accelerometer axis) is antiparallel to the computational frame. Any definition which is consistent in the computational frame, therefore, will have an opposite physical realization on one instrument. Definitions presented here are chosen to present a consistent computational frame definition.

Gyro channel bias drift sense is defined in the computational frame. A positive drift of a gyro channel is indicated by a gyro output of the same sign as would be caused by a positive rotation of the platform about the associated computational axes. Compensation for a positive drift term requires commanding negative torquing about that computational axis.

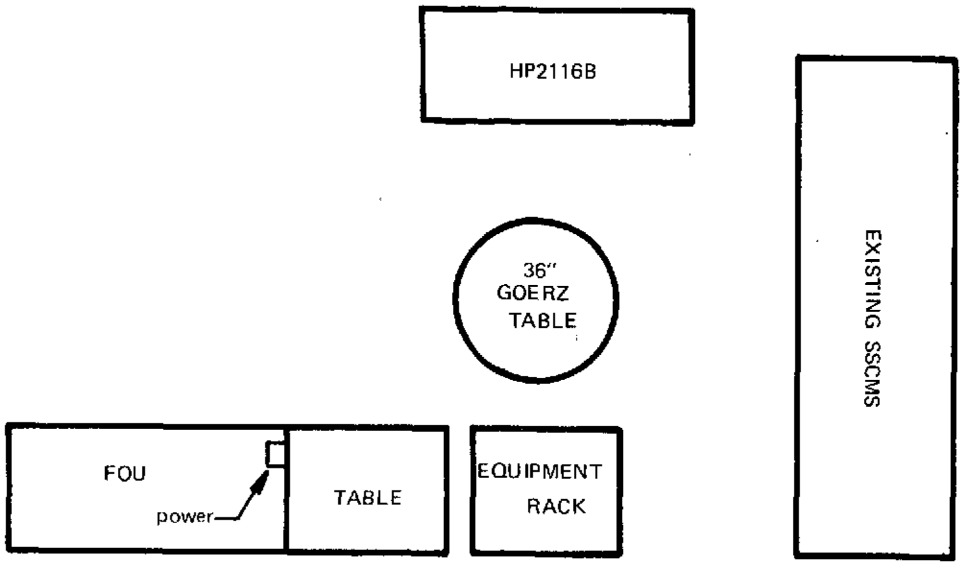
Acceleration- and acceleration-squared-sensitive drift error senses are defined similarly. A physical drift manifested as a real positive rotation and compensated for by negative torquing (in the computational frame) is termed positive. For the three acceleration-sensitive terms presently calibrated and compensated for in this system, a mass-unbalance term yielding positive drift in response to a positive specific force along some computational axis is termed positive.

Accelerometer inputs are defined such that, with the instrument mounted in the earth's gravity field with its IA up, +1g is indicated. Accelerometer bias resulting in CAPRI pulses in the same sense as a positive input is termed positive.

2.3 Test Laboratory Facilities

This test plan is to be carried out with the redundant IMU system coupled with NASA/MSFC's SSCMS. The three IMUs, with the APSs and IUs, are mounted on a 36" Goerz SDAT airbearing table.

Physical placement of system components is shown in Figure 2-3, Proposed Test Area Layout.



Equipment Rack:	Standard Electronics rack, to hold 28 VDC supply, PDB and PIU.
Table:	A table is required for the 4π-CP2, its auxillary memory and other equipment. Suggested dimensions 36" long by 30" deep by 32" high, with a 30" deep shelf 12" off the floor.
FOU:	Field Operating Unit for the 4π-CP2, 60" by 30" by 72".

Cable Length Constraints, given in cable run measurements, not necessarily straight paths. Goerz table to equipment rack: 20', with allowance for table motion. Rack to 4π-CP2: 24', fixed. 4π-CP2 Table to FOU: 2', fixed.

Power Requirements, given in cable run measurements, not necessarily straight paths. The PDB requires 115V60 Hz 1ϕ 30 amp max and 115 V 400 Hz 3ϕ 20 amp/phase max, both 20' from equipment rack. The 400 Hz power should be available on a Pass and Seymour P & S 7250 four wire polarized recepticle. The FOU requires 230 V 60 Hz 3ϕ 30 amp/phase max: 8' from FOU power recepticle. The 230 V power should be available on an Arrow and Hart A & H 20403 four wire recepticle.

Figure 2-3. Proposed Test Area Layout.

The Goerz table rotary axis is computer controllable (by the HP2116B) with respect to both rates and positions. Pure slews, ramp rates and sinusoidal oscillations may be commanded, and may be superimposed. Oscillatory capabilities are limited by servo characteristics dominated by the mass of the table plate and the redundant system mounted on it. Estimated excursions attainable are 10^{o} p-p at 1 Hz, falling off at approximately 40 db/decade for higher frequencies. Readout accuracies with the table in motion are approximately 10^{-4} degrees at low rates, with accuracies degrading to about 10^{-1} degree at rates greater than $10^{o}/s$.

It was intended that the Goerz table sliprings be used to carry analog test point signals to the SSCMS, as listed in Appendix A, CSDL Avionics Memo #74-3, Analog Test Point Listing for the Laboratory Demonstration Multiple IMU System. This capability, however, has not been implemented.

3.0 SYSTEM INTEGRATION AND FUNCTIONAL VERIFICATION

System hardware integration and functional verification at NASA/MSFC was carried out by CSDL personnel. Following verification, NASA/MSFC is now conducting acceptance tests. The bulk of this test plan concerns work following acceptance. This section, however, describes briefly the work required to integrate and checkout the system, and defines required periodic hardware checkouts.

3.1 System Integration

Work required to mount and rough align the system, verify all interfaces and signals and apply power will take about two weeks. System operational verification, which will include alignment and gyrocompassing, navigation and FDI demonstrations, will similarly entail about two weeks time.

These time estimates presume that all IMUs to be used in the multiple IMU system have been calibrated using Kearfott GSE, and are completely operable. Additionally, it is assumed that appropriate power is available as shown in Figure 2-3, Proposed Test Area Layout.

The first steps include verification of all electrical interfaces, mounting all equipment on the Goerz table and electronic racks. The outputs of the PDB will be verified.

The computer (and associated hardware) will be exercised to show proper operation. The system's 4π-CP2 interface and the data buses will be exercised, and demonstration of all commands and data transfers for each IMU will be made. The computer is powered-on and IBM's Computer Self-Check program is initiated and used to verify computer readiness. Upon completion of this task, Tape 1 is loaded. The typewriter I/O program is initiated. The data bus evaluation comprises verification of the ability to read from and write to each IU. Interfacing with each IMU will be examined individually. Analog gimbal slew tests including six slews (positive and negative about the X, Y, and Z axes) will be conducted for each IMU in sequence. During these tests the gimbal angle data (synchro/digital converter outputs) and CAPRI data will be displayed. Similar evaluation of digital slew commands, using the gyro pulse torque (GYPTO) logic, will be performed.

Determination of S/D deadzones has been made for each of the nine functional axes.

The 4π-CP2/HP2116B and the system/SSCMS interfaces will be verified. Data display and storage in the HP2116B will be exercised.

IMU #1 will be turned on via the power-on discrete and selection of the ground-align mode demonstrated. The operator will note a system ready discrete (indicator light on IU front panel) approximately two minutes from system turn-on. The IMU will then automatically be moded through a series of ten sequences to a stabilized ground align/gyrocompass condition. Synchro and accelerometer information will be displayed at the SSCMS' CRT (or the typewriter) in formats similiar to that shown in Appendix B, Multiple IMU System Typewriter Formats, Figures B-1, B-2.

When it is shown that IMU #1 is within the attitude tolerances, IMU #2 and IMU #3 will each in turn be turned on and "brought up" to the ground align/gyrocompass stabilized mode of operation.

These demonstrations are not intended to stand as either complete functional verification or as acceptance tests. Instead, they are intended to show proper system operation and to pave the way for the detailed functional testing to follow.

3.2 Functional Verification Outline

The complete verification of Tape 1 will now be accomplished. Ground alignment, gyrocompassing and land navigation will be exercised. Failure detection and isolation routines will be demonstrated.

Since the gimbal angle offsets and non-orthogonalities are not to be determined (other than a priori data supplied by the IMU manufacturer) it is necessary to obtain gimbal angle references (initializations) for the three IMUs from the available system modes. The ground align/gyrocompass (GRDAGYRC) program will be used. The computer memory will be loaded with current calibration constants and those navigation constants which are dependent on local latitude. GRDAGYRC will be initialized and the IMUs allowed to stabilize. Gimbal angle outputs will be observed and documented for reference.

Fine mechanical alignment of the three IMUs will be undertaken at this point.

The system will be placed in Land Navigation after it has been gyrocompassed. Navigation performance will be monitored by the HP2116B, with downlink data corresponding to the FDI/Navigation Typewriter Format shown in Figure B-3.

Failure detection and isolation software will be exercised. Algorithms based upon velocity and upon attitude information will be demonstrated, both with three colinear and two skewed IMUs. System reconfiguration routines will be demonstrated.

The following section constitutes a short description of delivered software and a manual of system operation describing in detail the broad demonstrations listed above.

3.3 System Software Overview

3.3.1 Introduction

The software is delivered in the following forms:

(1) IBM 4π-CP2 source language card decks and IBM/System 360 link card decks.
(2) Program descriptions and flowcharts (See Volume III of this report, Multiple IMU System Software Design and Coding).
(3) Two sets of punched aluminized mylar object tapes

The object code on mylar tape is in two parts, representing FDINAV (on Tape 1) and IMUCAL (on Tape 2). Each of these tapes contains common system programs, including the Executive and typewriter operating system. The FDINAV tape also provides the capability to perform

(1) Ground alignment
(2) Gyrocompassing
(3) Navigation
(4) Colinear and Skewed FDI with redundancy management

The IMUCAL tape provides the ability to estimate 19 instrument compensation parameters for each IMU. Calibration is performed for the three IMUs, sequentially, without manual intervention. Only a single set of tapes can be loaded in a test sequence.

3.3.2 Tape Loading and Initialization Procedure

The following procedures assume the IBM 4π-CP2 is connected to a Field Operating Unit (FOU). If any other computer GSE is used, the operator must perform a corresponding function for that equipment. With FOU power, 4π-CP2 power and auxiliary power on:

(1) Mount and thread first reel of desired tape (either FDINAV or IMUCAL) on the FOU's REMEX tape reader.
(2) Switch tape reader rewind OFF and power ON.
(3) Set MODSEL to STORE.
(4) Set LOAD switch to TAPE. All other FOU switches are OFF.
(5) Depress TAPE ADV and wait until first data frame is under photo reader.
(6) Depress TAPE START and wait until all data is read and leader is visible in the photo reader. Switch tape reader power OFF.
(7) Depress STOP.
(8) Switch tape reader rewind and power ON and wait until all tape has been retrieved.
(9) Turn tape reader rewind and power OFF and remove the reel.
(10) Repeat this process (steps 1 to 9) until each reel has been read. Each tape set as delivered consists fo three (5.5 inch diameter) reels, two of which are full, the remaining one being partially full.

The rest of this procedure should be employed (with noted exceptions) whenever the system is started, regardless of whether a new tape has been loaded. It is suggested that tapes should be loaded only when required, e.g., when switching from FDINAV to IMUCAL or vice versa.

(11) The following switch modes should be verified or selected:

REPEAT-OFF (or down)
BADPARITY-OFF (or down)
STOR PROT-OFF (or down)
INH INT-OFF (or down)
INH I/O INT-OFF (or down)
STOR PROT KEY-ON (or up)
LOAD-MAN (or down)
MODE SEL-RUN

(12) Depress CHECK RES.
(13) Turn typewriter ON.
(14) Depress SYSTEM RES. At this time a "!" will be typed.
(15) Depress the ABORT button on the FOU, initializing the PIU. The message "! ABT, 00" will be typed. The system will now be running and the

typewriter operating system ready to accept operator requests.

(16) If a new tape has been loaded, the calibration parameters for the three IMUs must be loaded at this point. These are loaded using the FIX, typewriter command or a tape dump of a previous load. The values are those determined at the last calibration (as printed by IMUCAL under the heading AFT) and are entered into the locations stated below. It is emphasized that absolute addresses given in this text refer only to the assembled programs as delivered on Tape 1. In any subsequent assembly, new absolute addresses must be determined.

0A38-DXRA for IMU 1, 2, 3
0A3E-DYRA for IMU 1, 2, 3
0A44-DZRA for IMU 1, 2, 3
0A5C-KGX for IMU 1, 2, 3
0A62-KGY for IMU 1, 2, 3
0A68-KGZ for IMU 1, 2, 3
0A6E-KLX for IMU 1, 2, 3
0A74-KLY for IMU 1, 2, 3
0A7A-KLZ for IMU 1, 2, 3
0A80-KHX for IMU 1, 2, 3
0A86-KHY for IMU 1, 2, 3
0A8C-BLX for IMU 1, 2, 3
0A92-BLY for IMU 1, 2, 3
0A98-BLZ for IMU 1, 2, 3
0A9E-BHX for IMU 1, 2, 3
0AA4-BHY for IMU 1, 2, 3
0AAA-ADIX for IMU 1, 2, 3
0AB0-ADIY for IMU 1, 2, 3
0AB6-ADIZ for IMU 1, 2, 3

"Case" values of these parameters may be used in lieu of a more recent calibration. These numbers must be scaled properly and entered in fixed point format. Appendix C, Converting "Case" Values to Internal Formats, defines this conversion.

(17) If any patches or data changes are required, they are made at this point using the typewriter functions; HSP, HEX, INT, FIX, EXP,.

3.4 System Functional Verification

3.4.1 Verification Aids

All system I/O functions can be controlled and monitored using the facilities of TYPIO. The commands CMD, CAP, SYN, STS, GYP, are used to control the IMU I/O. The DMP, HEX, INT, commands are useful in monitoring IMU inputs. In addition, a special sequence, MONITR, exists which will periodically sample and print IMU I/O registers. Normally, the registers are sampled and printed every 60 seconds in an integer format. The registers printed are:

> 3 IMU status registers, 3 X synchros, 3 Y synchros, 3 Z synchros, 3 X CAPRIs, 3 Y CAPRIs, 3 Z CAPRIs and 3 IMU command words.

The MONITR program can be modified (from this version as it appears in the software tapes) by simple patches, which are described here these addresses will presumably change in any new assembly. (Specific hex addresses quoted are for the delivered Tape 1). One application of MONITR used frequently in what follows is to print only the gimbal angles and CAPRI counts, for a single IMU, at short intervals.

For this application, a common area is used to hold data for printing. IMUs not being monitored are failed, as explained in Section 3.4.2 below. The locations used are:

0804 to 0806 hex: Pitch, Roll, Azimuth Angles
080A to 080C hex: CAPRIX, CAPRIY, CAPRIZ

MONITR must be prepared with the following data:

NAME	LOCATION	FUNCTION
DELTAT	7B76	$>8_{10}$. Time interval between printouts in seconds.
KIND	7B77	Printout format: 0 implies hex numbers, 1 implies integer numbers, 2 implies fixed point numbers, and 3 implies floating point numbers.
HPLIST	7B78	List of from, to addresses. Up to six sets may be specified. The list is terminated with two halfwords words of all ones (HEX, FFFF).

SMALLT	7B89	=0
SECS	7B8A	=0
RECFIN	7B8B	=0

Another display format which is available is the histogram program. This program will generate an in core histogram of a single data item, either CAPRI readings or delta synchro readings. At termination, the in core class intervals may be displayed using the INT, or DMP, function, or the histogram may be printed in its entirety using the MONITR program. The histogram program is a minor cycle task, and can be added to any sequence minor cycle task list. The MONITR minor cycle list is an appropriate sequence.

A number of registers must be intialized for proper operation. These are:

NAME	LOCATION	FUNCTION
MIDPT	3360	Reference value, i.e., the expected midpoint.
HWIDTH	3361	One half the desired class interval width.
KIND	3362	Data type: 0 implies delta synchro readings 1 implies CAPRI readings.
CTR	3363	= 0 Counter which must be initialized at zero for each run.
ADDR	3364	Address of the data point.

The following is a list of synchro and CAPRI data addresses:

09FE	X S/D output, IMU 1
09FF	X S/D output, IMU 2
0A00	X S/D output, IMU 3
0A01 - 0A03	Y S/D outputs, IMUs 1, 2, 3
0A04 - 0A06	Z S/D outputs, IMUs 1, 2, 3
0A07 - 0A09	X CAPRI outputs, IMUs 1, 2, 3

0A0A - 0A0C	Y CAPRI outputs, IMUs 1, 2, 3
0A0D - 0A0F	Z CAPRI outputs, IMUs 1, 2, 3

Locations 336C through location 33AE contain the class interval values at the termination of the program, with the mid point at location 338D.

The MONITR sequence may be used to run the histogram program by setting location 7BDE equal to 33B4 (the initial address of Histogram). If it is desired to sample data at a faster rate (faster than 5 Hz) the following locations should also be loaded with the initial address of histogram: 7BDC, 7BEO, 7BE2 and 7BE4.

When all registers have been initialized, the procedure for running histogram is:

HEX,3363	CR
0	CR
CAP,1	CR
SEQ,MONITR	CR
RUN,	CR

The run is terminated via the ABORT button on the FOU.

One additional tool available for use in verifying system operation is the miscompensation routine, MISCTAB, which may be used to simulate soft failures (performance degradations). The soft errors are simulated as follows: at a specified time during a test, the miscompensation routine will alter the compensation parameters (scale factor or bias for CAPRI failures, gyro torquing scale factor and gyro compensation parameters for the gimbal angle failures) of a specified instrument of a specified IMU by a specified amount. These quantities are obtained from the table MISCTAB which is entered manually via the typewriter prior to initiating the test. The table has the following format:

MISCTAB+0, +1	- $TIME_O$
MISCTAB+2, +3	- VAL_O
MISCTAB+4	- ADD_O
.	.
.	.
.	.
.	- $TIME_n$
.	- VAL_n
.	- ADD_n

where $TIME_n$ is the time (centi-sec, B31) from the beginning of the FDI/Navigation mode at which the quantity VAL_n will be added to the compensation parameter whose address is ADD_n. This quantity is added in only once. n is limited to five maximum.

In the particular case of CAPRI bias terms, MISCTAB should not change the bias term itself but the new variable BLiDT = 0.2 BLi. These terms are scaled as are the bias terms, and are in locations

BLXDT	IMU1	OACO
BLXDT	IMU2	OAC2
BLXDT	IMU3	OAC4
BLYDT	IMU1	OAC6
BLYDT	IMU2	OAC8
BLYDT	IMU3	OACA
BLZDT	IMU1	OACC
BLZDT	IMU2	OACE
BLZDT	IMU3	OADO

A typical use of the miscompensation routine would be this. In a test of the colinear, attitude-based FDI, IMU1 X channel bias drift (ADD_o) is altered at $TIME_o$ by some value (VAL_o), say 0.5^o/hr. The overall effect on the system, then, would be precisely that of a step change in DXRA.

3.4.2 Verification of IMU Commands and Data Demands

All the IMU commands may be initiated from the typewriter using the function CMD,. The format is

CMD, i, j

where i=1, 2, 3 designating the IMU and j is such that

$$-16 < j < 19$$

excluding zero.

If j=1, 2, . . . , or 16 then the corresponding bit of the appropriate command register is set (ICMAND, +1, +2 of TYPIO). If j is negative then the bit is cleared. See Table 3-1, Command Register Bit Assignments, for bit definitions. The value j=17 causes the chosen command register to be sent to its IMU. j=18 will fail the IMU and j=19 will restore a failed IMU. Alternatively, the registers "ICMAND" of TYPIO

Table 3-1. Command Register Bit Assignment (ICMAND)

BIT	FUNCTION	
1	(Grid Mode) NOT IMPLEMENTED	
2	(Mag Slave Mode) NOT IMPLEMENTED	
3	Inertial Mode	(1 = set)
4	Normal Mode	(1 = set)
5	Ground Align Mode	(1 = set)
6	Reset Fail Flip Flop	(1 = reset)
7	Reset Fail Indication	(1 = reset)
8	Computer Control	(1 = true)
9	Computer Fail	(1 = true)
10	CAPRI Scale Factor	(0 = low gain, 1 = high gain)
11	X Slew Sense	(0 = positive, 1 = negative sense)
12	X Slew	(1 = slew)
13	Y Slew Sense	(as above (11))
14	Y Slew	(as above (12))
15	Z Slew Sense	(as above (11))
16	Z Slew	(as above (12))

There is a sixteen bit word assigned as ICMAND for each IMU_i, i = 1, 2, 3. These are the locations (in the present assembly):

IMU	Address	Hex Address
1	ICMAND	7 AF0
2	ICMAND + 1	7 AF1
3	ICMAND + 2	7 AF2

Bit 16 is the low orderbit. The command can be written as a 4 character hex number. Thus hex 2000 commands Inertial mode and nothing else. Slew sense is significant only if a slew is commanded.

may be loaded using the HEX, function. Again, it is to be noted that absolute addresses refer only to the delivered assembly.

Reference will also be made to information contained in IUSTATS, the status register for each IMU. The bit assignment for these registers appear in Table 3-2, IMU Status Register Bit Assignments.

3.4.2.1 Slew Test

The purposes of the slew test are to verify the ability to command analog slew of both senses about any of the computational axes, and to determine slew rates. Nominal rates are:

X and Y, 1800±360 degree/hour, azimuth, 5400±1080 degree/hour.

(1) Set up command register to slew IMU 1 in azimuth (or, about Z_c):

```
HEX,7AFO      CR
   2701       CR
   #          CR
```

where 7AF0 is address of command register for IMU 1. ICMAND=2701 will put IMU 1 in inertial mode, reset failures, set computer control and set azimuth slew with sense zero (increasing gimbal angle).

(2) Send command word to IMU:

```
CMD,1,17      CR
```

(3) Read synchros, CAPRIs:

```
SYN,1         CR
CAP,1         CR
```

(4) Initiate MONITR to display synchros and CAPRIs:

```
SEQ,MONITR    CR
```

(5) Run MONITR:

```
RUN,          CR
```

(6) Observe increasing azimuth synchro angle, and that CAPRI outputs remain zero on the X_c and Y_c axes and +1g on Z_c.

(7) Terminate by depressing ABORT button on the FOU.

This test can be performed for each axis of all IMUs under both slew sense conditions. Table 3-3, Calls to Analog Slew, lists the equivalent commands for these additional tests.

Note that in the synchro register, a low order bit is worth 20 $\widehat{sec}$ (although the 80 $\widehat{sec}$ bit is the least significant bit sent to the computer). In the CAPRI register (LO gain condition) a bit is worth approximately 1 cm/s.

Table 3-2 IMU Status Bit Assignments (IUSTATS)

BIT	FUNCTION
1	GYPTO write fail
2	Synchro read fail
3	Status read fail
4	CAPRI read fail
5	Command write fail
6	BITE fail
7	Attitude FDI fail
8	Velocity FDI fail
9	System ready
10	Inertial mode
11	Ground Align Mode
12	X slew in progress
13	Y slew in progress
14	Z slew in progress
15	Hard Fail*
16	Soft Fail*

There is a sixteen bit word assigned as IUSTATS for each IMU_i, $i = 1, 2, 3$. These are the locations (in the present assembly):

IMU	Address	Hex Address
1	IUSTATS	09 FB
2	IUSTATS + 1	09 FC
3	IUSTATS + 2	09 FD

Bit 16 is the low order bit. Thus, status can be expressed as a 4 character hex number. 004C, as one example, would indicate that no failures have been detected, the IMU is in the inertial mode, and that it is slewing about both Y and Z gyro axes.

*A hard failure is caused by persistent PIU read/write failure, BITE failure or data reasonableness test failure, and implies termination of all processing of that IMU. A soft failure is caused by recognition of a failure by software FDI. In this case, the IMU data will not be used in navigation.

Table 3-3. Calls to Analog Slew

Positive X Slew	HEX, 7AFØ CR 271Ø CR # CR	HEX, 7AF1 CR 271Ø CR # CR	HEX, 7AF2 CR 271Ø CR # CR
Negative X Slew	HEX, 7AFØ CR 273Ø CR # CR	HEX, 7AF1 CR 273Ø CR # CR	HEX, 7AF2 CR 2730 CR # CR
Positive Y Slew	HEX, 7AFØ CR 27Ø4 CR # CR	HEX, 7AF1 CR 27Ø4 CR # CR	HEX, 7AF2 CR 27Ø4 CR # CR
Negative Y Slew	HEX, 7AFØ CR 27ØC CR # CR	HEX, 7AF1 CR 27ØC CR # CR	HEX, 7AF2 CR 27ØC CR # CR
Positive Azimuth Slew	HEX, 7AFØ CR 27Ø1 CR # CR	HEX, 7AF1 CR 27Ø1 CR # CR	HEX, 7AF2 CR 27Ø1 CR # CR
Negative Azimuth Slew	HEX, 7AFØ CR 27Ø3 CR # CR	HEX, 7AF1 CR 27Ø3 CR # CR	HEX, 7AF2 CR 27Ø3 CR # CR

3.4.2.2 CAPRI Scale Factor Test

The purpose of this test is to verify the reasonableness of X and Y CAPRI scale factors at high gain, thus the ability to command high gain.

(1) Cause built in leveling of IMU

STOP computer.

Turn IMU power off.

Wait 5 minutes. Turn IMU power on.

Depress System Reset on the FOU.

Depress ABORT on the FOU.

(2) Initialize command words for all IMUs to slew $+5^{\circ}$ about X:

HEX,7AFO	CR
2704	CR
2704	CR
2704	CR
#	CR

(3) Start all slews:

CMD,1,17	CR
CMD,2,17	CR
CMD,3,17	CR

(4) After 3 seconds, stop slewing by depressing ABORT on the FOU.

(5) Command all IMUs to inertial and computer control, and low gain CAPRI scale factor:

HEX,7AFO	CR
2700	CR
2700	CR
2700	CR
#	CR
CMD,1,17	CR
CMD,2,17	CR
CMD,3,17	CR

(6) Read all CAPRIs:

CAP,1	CR
CAP,2	CR
CAP,3	CR

(7) Interrogate Y CAPRI registers (IMUCAPRY, +1, +2 of EXEC) using the INT, function:

INT,0A0A	CR
	CR (displays YCAP1)

CR (displays YCAP2)
CR (displays YCAP3)
\# CR (terminates display)

The Y CAPRI counts will be approximately 80-100 pulses at low gain, that is, g $\sin\theta$ in 1.0 cm/s/pulse units. The IMUs are now changed to high gain.

```
HEX,7AFO    CR
    2740    CR
    2740    CR
    2740    CR
       #    CR
CMD,1,17    CR
CMD,2,17    CR
CMD,3,17    CR
```

The IMUCAPRY counters are again interrogated:

```
INT,0A0A    CR
            CR (displays YCAP1)
            CR (displays YCAP2)
            CR (displays YCAP3)
       #    CR (terminates display)
```

The value of all Y CAPRIs should be about 8000-10000 (or g $\sin 5^{\circ}$) in high gain units (.01 cm/s/pulse).

This procedure can be used for positive and negative rotations on both X and Y axes.

3.4.2.3 GYPTO Test

It is somewhat difficult to perform precise tests of the GYPTO from the typewriter because of earth rate sensed by the instruments. Limited verification can be performed using the GYP, function:

$$\text{GYP, i, } j_X, j_Y, j_Z$$

i= 1, 2, 3, indicating the IMU. The j is an integer period between GYPTO pulses in minor cycle units (20 ms). Thus j_X = 1 will torque the X gyro at a rate of (0.4 $\widehat{sec}$/.02s) = 20 deg/hr. Torquing sense corresponds to the sign of j.

3.4.2.3.1 Azimuth Gyro

The azimuth torquing can be tested by torquing plus and minus and measuring difference in azimuth gimbal rates. That is, if ω_B = azimuth bias drift plus earth rate component, and ω_{GZ} = + 20^{o}/hour, then measure gimbal rate $\omega_0 = \omega_B + \omega_{GZ}$ due to positive input, and $\omega_1 = \omega_B - \omega_{GZ}$ and the difference

$$\omega_0 - \omega_1 = 40^{o}/hr$$

(1) With the platforms level, place IMUs in inertial mode and computer control as before (ICMAND=2700).

(2) Initiate +20^{o}/hr rate on Z and very small rate on X and Y of all IMUs:

```
GYP,1,10000,10000,1        CR
GYP,2,10000,10000,1        CR
GYP,3,10000,10000,1        CR
```

(3) Read synchros for all IMUs:

```
SYN,1                      CR
SYN,2                      CR
SYN,3                      CR
```

(4) Initiate MONITR:

```
SEQ,MONITR                 CR
```

(5) Run MONITR:

```
RUN,                       CR
```

(6) Observe difference in azimuth synchros in different printouts, dividing by the time increment to determine the rate ω_0.

(7) Terminate by depressing the ABORT button on the FOU.

(8) Perform this same procedure (1-7) using negative rate (i.e., GYP,1,10000,10000,-1 CR) to establish ω_1.

(9) Compute the difference in gimbal rates and compare it to 40^{o}/hr.

3.4.2.3.2 Level Gyros

It is more convenient to use CAPRI data (at high gain) to verify the torquing performance of the level gyros. This verification is based on the equations:

ΔV_{X0} = ΔV(over 0.2s) at some position near X axis
ΔV_{X1} = ΔV(over 0.2s) at the position of the X axis after ΔT seconds torquing about Y.

$$\omega_{gy} = \frac{\Delta V_{x1} - \Delta V_{x0}}{0.2g \quad \Delta T}$$

A similar equation in ΔV_Y is used for ω_{gx}, with the test performed with the platform level and azimuth at $+90^o$ to eliminate earth rate contributions. The data rate required for this test limits MONITR to one IMU's data. Commands shown here will perform the test on IMU 1.

(1) Level the platform with X North.

(2) Set up command for inertial mode, computer control and high CAPRI gain for the IMU:

HEX,7AFO	CR
2740	CR
#	CR

(3) Set up GYPTO command for Y gyro torquing at a positive fixed rate (+ 20^o/hr), initiate MONITR, and issue the command:

GYP,1,10000,1,10000	CR
CAP,1	CR
SEQ,MONITR	CR
CMD,1,17	CR

(4) Run MONITR:

RUN,	CR

(5) After 100s, terminate using the ABORT button on the FOU.

It is to be recalled that MONITR, used in this mode, prints:

0s	Pitch S/D	Roll S/D	Azimuth S/D	CAPRIX	CAPRIY	CAPRIZ
10s	"	"	"	"	"	"
20s	"	"	"	"	"	"

The CAPRI reading at zero may be taken as ΔV_{io} when scaled. A convenient interval, say Δt = 100s, is allowed to pass, and ΔV_{i1} is read. Then, for the first test,

$$\omega_{gy} = \frac{(\text{CAPRIX}_1 - \text{CAPRIX}_0)(0.01 \text{ cm/s/pulse})}{(0.2\text{s})(g \text{ cm/s}^2)(\Delta t \text{ s})}$$

3.4.3 Verification of HP2116B/4π-CP2 Interface

A special sequence exists, "TYPWIO," which is a version of the typewriter operating system which also sends IMU data across the HP2116B/4π-CP2 interface. This sequence can be used to verify downlink. No test for verifying transmission of data in the other direction is described because the ability to do this does not now exist on either Tape 1 or Tape 2.

(1) Instruct the operator of the HP2116B that the 4π-CP2 will be sending the default data list (CODE = 0). Wait until the HP2116B is prepared to receive and display this data.

(2) Manually load the following registers in the EXEC with constant data:

"IMUGMBX"	9 half words corresponding to the 9 gimbal angles (least significant bit = 20 sec)
"IMUCAPRX"	9 half words corresponding to 9 CAPRI registers (least significant bit = 1 cm/s)
"IUSTATS"	3 half word status registers (binary)
"TIME"	1 full word representing time (least significant bit = .01 seconds)

(3) Initiate and run TYPWIO:

```
SEQ,TYPWIO      CR
RUN,            CR
```

(4) Observe the display of down link data at the HP2116 terminal.

(5) The above referenced data may be dynamically altered by using the HEX, INT, etc., functions. In each case, determination will be made that the displayed data in fact shows the changes made at the typewriter.

3.5 System Software Procedure and Verification (Tape 1)

The Tape 1 system software consists of ground alignment, gyrocompass, navigation, colinear attitude FDI, colinear velocity FDI, skewed FDI and redundancy management. This section will describe procedures for operating and verifying these software units. The purpose of this verification is to ensure system integrity and to provide base line data prior to FDI algorithm evaluation.

3.5.1 Ground Alignment

Ground alignment (program GALGN) computes two bias drifts for the level gyro and coarse alignment in azimuth for the IMUs prior to gyrocompassing. At termination of ground alignment, the system immediately commences gyrocompassing. Verification of ground alignment is based on run to run stability of computed bias drifts as well as the terminal azimuth error. These parameters should be recorded for each run.

(1) Manually align the table so that all case "FORE" axes are pointed North.

(2) Power up IMUs and wait for System Ready lights. At this point, the platforms will be approximately level. Slew in azimuth all IMUs (using

CMD, function) until each azimuth synchro reads zero.

(3) Select the Ground Align sequence:

SEQ,GRDALN	CR
RUN,	CR

(4) Record the computed bias drifts and compare with calibration values as well as the mean and variance of previously recorded drifts.

Various messages will be printed at the FOU typewriter indicating the start of alignment sequences. These are:

MSG,00	Minus 90 degree azimuth slew
MSG,01	Rapid erection of platform
MSG,02	Rapid erection of platform
MSG,03	Refinement of platform level.

There will be sixteen refinements prior to sequence 4 and five more refinements prior to sequence 9.

MSG,04	Azimuth error measurement
MSG,05	Azimuth error correction
MSG,06	Y gyro calibration
MSG,07	Positive 90 degree slew
MSG,08	Relevel and stabilization
MSG,09	X gyro calibration
MSG,10	Termination of Ground Align and start of gyrocompass

The total time required for ground alignment is approximately 20 minutes. This may vary because of differences in the time required to correct level and azimuth errors. Ground alignment may be terminated by depressing the ABORT button on the FOU.

3.5.2 Gyrocompass

Gyrocompass (program GYRCMP) maintains platform level as well as driving the azimuth so as to reduce the north velocity to zero. This process follows ground alignment and will continue for 45 min. No separate sequence command is required.

(1) If a time interval other than 45 min is desired, load that time (centi-secs, scaled B31) into location GCTIME (location 305C) prior to initiating the GALGN sequence. Gyrocompassing may also be terminated by means of a switch on the PIU which causes transition into FDINAV.

(2) During gyrocompassing, verify that the north velocity tends toward zero and that the platform obtains a stable, level and north pointing configuration.

(3) Note the platform position at the end of gyrocompassing and compare it with previous runs.

At the end of the programmed time interval, gyrocompassing will end and FDI/Navigation will commence. The sequence may be aborted during gyrocompassing by pressing the ABORT button on the FOU.

3.5.3 FDI/Navigation

FDI/Navigation will be entered automatically at the completion of gyrocompassing. It is also possible to initiate this mode manually by typing

```
SEQ,FDINAV      CR
RUN,            CR
```

However, since acceptable navigation performance requires the IMUs to be ground aligned and gyrocompassed, all tests requiring navigation should be started with

```
SEQ,GRDALN      CR
RUN,            CR
```

The type of FDI test desired (if any) may be selected by initializing the items FDIFLG (location 302A) and NEWFAIL (location 302E) and by hard failing (via the CMD function) the appropriate IMU prior to the selection of the Ground Align sequence:

(1) <u>FDIFLG = 0</u>

Navigation will be performed with no FDI processing

(2) <u>FDIFLG = 1, No hard failed IMUs</u>

Navigation will be performed with Colinear Velocity FDI (program VFDI) processing. Upon detection and isolation of a failure, the two remaining IMUs will be commanded to the skewed configuration and skewed FDI processing commenced.

(3) FDIFLG = 2, No hard failed IMUs

Same as (2) above except Colinear Attitude FDI (program AFDI) processing will be performed.

(4) FDIFLG=0, NEWFAIL=m (IMU 'm' hard failed)

Upon entering the FDI/Navigation Mode the two remaining IMUs will immediately be placed in the skewed configuration and skewed FDI (programs TWOVFDI and TWOAFDI) processing started. Navigation is also performed.

3.5.3.1 Navigation

Navigation employs inertially stabilized (and not locally level) platforms with the platform computational frames initially in the North, West and Up position attained by gyrocompass. Verification is based mainly on latitude and longitude error monitoring.

(1) Verify that latitude and longitude errors remain within acceptable limits.
(2) Verify that these errors exhibit an 84 min Schuler period.

Navigation may be performed using any subset of the three IMUs. Performance must be investigated with three colinear platforms, with two skewed platforms and with a single platform either aligned to the (North, West, Up) frame or skewed relative to it. In each case, the same navigator performance may be expected, and identical evaluations are made.

3.5.3.2 FDI Redundancy Management

There are two general types of errors that may be detected by the FDI logic: "hard" IMU errors and "soft" performance errors. The hard IMU errors consist of the IMS FAIL discrete set and a reasonability check made prior to any processing to verify that gimbal angle rates are under 20°/second and each velocity output register indicates under 2000 cm/s^2. (With the system CAPRIs in high gain, the velocity reasonability limits on the X and Y axes are 200 cm/s^2.) "Hard" errors will be detected at any time during a test. "Soft" errors will only be detected during the FDI/Navigation mode. Hard error detection and isolation results in the affected IMU's being placed off-line and removed from all further processing. Soft error detection and isolation results in the effected IMU's being removed from Navigation processing only. All other processing (CAPRI and gimbal angle reading, torquing, etc.) will continue.

Hard error FDI operation may be verified as follows:

(1) Initiate hard IMU failure via the IMS FAIL discrete switch provided at the IU. This hard failure simulation may be done at any time in the test (ground alignment, gyrocompass) and not necessarily in the FDI/ Navigation mode. Hard failure detection and isolation is indicated by one of the following typewriter printouts:

ERR, "ab" (a=5, 6, 7; b=1, 2, 3)
Gimbal hard failure on gimbal axis 'a', IMU 'b' where
5=Roll, 6=Pitch, 7=Yaw.
ERR, "cd" (c=0, 1, 2; d=1,2,3)
CAPRI hard failure on accelerometer axis 'c',
IMU 'd' where 0=X axis, 1=Y axis, 2=Z axis.

(2) Verify that the above printouts correspond to instrument and IMU hard failed and that IMU is taken off-line (bit 15, 16 of applicable status word are set).

(3) If the hard failure is initiated during FDI/Navigation mode with three IMUs on-line, verify the slewing of the remaining IMUs into a skewed configuration and initiation of the skewed IMU FDI.

Soft performance error FDI may be verified as follows:

(1) The soft errors are simulated as follows: At a specified time during a test, a miscompensation routine will alter the compensation parameters (scale factor or bias for CAPRI failures, gyro torquing scale factor and gyro compensation parameters for gimbal angle failures) of a specified instrument of a specified IMU by a specified amount. These specified quantities are obtained from the table MISCTAB which is manually entered via the typewriter prior to initiating the test. The table MISCTAB has the following format:

MISCTAB +0, +1 — TIME: Time of parameter change (integer number of centi-seconds)
MISCTAB +2, +3 VAL: Change in loaded parameter, scaled as in Appendix C (Fixed point)
MISCTAB +4 ADD: Address of parameter to be changed (hex)

$TIME_n$ is the time (centi-sec) from the beginning of the FDI/Navigation mode at which the quantity VAL_n will be added to the compensation parameter whose address is ADD_n. This quantity is added in only once.

Up to five ($TIME_n$, VAL_n, ADD_n) sets may be given. (See Section 3.5.4 for example of the use of MISCTAB.) Colinear velocity FDI for 3 IMUs has two levels of failure detection: 3σ and red line. Only when a red line failure has been detected and isolated will the failed IMU be soft failed and removed from navigation processing. Failure detection and isolation are indicated by the following typewriter printouts:

Colinear Velocity FDI

ERR,jC 3σ failure detected on axis j
ERR,iD 3σ failure isolated to IMU i
ERR,jE - Redline failure detected on axis j
ERR,jF - Redline failure isolated to IMU i

Colinear Attitude FDI

ERR,jA - Attitude error detected on axis j
ERR,iB - Attitude error isolated to IMU i
where i = (1,2,3) is the IMU number and j = (1,2,3) corresponds to axis (X,Y,Z).

Skewed IMU FDI

ERR,81 - Velocity failure detected
ERR,82 - Attitude failure detected
ERR,ji - Failure isolated to IMU i, axis j
where i = (A,B,C) corresponds to IMU number (1,2,3) and j = (A,B,C) corresponds to axis (X,Y,Z). While slewing to the two skewed IMU configuration, the following printouts will be observed:

MSG,EB - IMU 2 starting to slew
MSG,EC - IMU 3 starting to slew
MSG,FB - IMU 2 slewing ended
MSG,FC - IMU 3 slewing ended

(2) Verify that any error printout corresponds to that intended from the contents of the miscompensation table MISCTAB.

(3) Verify the corresponding error detection and isolation ratios on the downlink.

(4) If an error occurs during colinear FDI, verify that the remaining two IMUs are placed in the skewed IMU configuration.

3.5.4 Example

The following example will illustrate the initialization procedures for a typical test.

Test desired:

Ground align and gyrocompass three colinear IMUs for one hour. Ten minutes into FDI/Navigation initiate a velocity channel bias redline failure on the X axis of IMU 3. Twenty minutes later initiate an attitude failure condition on the Y axis of IMU 2.

Initialization:

1. Manually align the IMUs so that their "FORE" axes point North
2. Power up IMUs, observing "System Ready" lights.
   Individually slew each IMU in azimuth until its azimuth angle reads zero.
3. Place all IMUs on line:
   CMD,1,19 CR
   CMD,2,19 CR
   CMD,3,19 CR
4. Initialize items as follows:
   GCTIME = 360000 cs (gyrocompass time, location 305C)
   FDIFLG = 1 (colinear velocity FDI for 3 IMUs, location 302A)
   MISCTAB+0, +1 = 60000 cs (time for 1st failure)
   MISCTAB+2, +3 = x (value to be added to low gain CAPRI bias (BLXDT) for X axis of IMU 3, scaled as in Appendix C)
   MISCTAB+4 = 0AC4 (address of the scaled CAPRI bias for the X axis of IMU 3)
   MISCTAB+6, +7 = 180000 cs (time for 2nd failure)
   MISCTAB+8, +9 = Y (value to be added to gyro torquing scale factor of Y axis gyro on IMU 2, scaled as in Appendix C)
   MISCTAB+10 = 0A64 (address of above gyro torquing scale factor)
5. Start the test:
   SEQ,GRDALN CR
   RUN, CR

Printouts:

In addition to the ground align printouts, the following printouts should be observed in FDI/Navigation:

ERR,1C - 1st failure 3σ detection
ERR,3D - 1st failure 3σ isolation
ERR,1E - 1st failure redline detection
ERR,3F - 1st failure redline isolation

MSG,EB - IMU 2 slewing to skewed configuration
MSG,FB - IMU 2 in skewed configuration
ERR,82 - 2nd failure in attitude is detected
ERR,BB - 2nd failure is isolated.

3.6 System Software Procedure and Verification (Tape 2)

The IMUCAL program, written for an IBM 4π-CP2 digital computer, is designed to compute 19 instrument calibration parameters for a Kearfott KT-70 IMU. Up to three KT-70s may be calibrated serially. IMUCAL, and the necessary EXEC and TYPIO functions, constitute Tape 2.

3.6.1 Loading Memory of IBM 4π-CP2

See Section 3.3.2 (Tape Loading and Initialization Procedure)

3.6.2 Converting "Case" Values to Internal Data Formats

The 19 calibration parameters are used in real time instrument compensation by the Executive during ground alignment, gyrocompass, FDI and navigation. Because of timing considerations during these modes, it is necessary to perform these compensations using fixed point arithmetic. Thus, if "case" values are to be loaded into 4π-CP2 memory, they must be converted to fixed point format. A table of conversion values to be applied to each parameter is presented in Appendix C. Converted parameters should be loaded into the indicated addresses using the FIX, command. Note that these are in consecutive full word locations.

3.6.3 Normal Starting Procedures

All case axes should be nearly parallel, and the rotary table should be positioned such that all "FORE" axes are pointed north. The system should be powered down and up again (after a brief period) to enable the internal coarse leveling. Each IMU should be slewed individually in azimuth to a zero gimbal angle, using the procedure in Section 3.4.

(1) All IMUs must be cleared of any hard failures, using

CMD,1,19	CR
CMD,2,19	CR
CMD,3,19	CR

(2) Select and start IMUCAL

SEQ,IMUCAL	CR
RUN,	CR

The 19 parameters for each IMU will be computed, and switching among IMUs will be automatic. During these sequences data, error codes and message codes will be printed on the FOU typewriter.

3.6.4 Typewriter Printouts

The following messages will be printed:

MSG,3i- The calibration sequence has started for IMU i, i=1,2,3
MSG,4i- The calibration sequence has been completed for IMU i, i=1,2,3
MSG,20- All calibration sequences have been completed

At the end of calibration for each IMU (after MSG,4i) a table of data indicating before and after values, in the fixed point format employed by EXEC, is printed.

If during processing a BITE failure or lack of "system ready" is sensed, then one of the following error messages is printed. Calibration for the indicated IMU will be terminated and then initiated on the next IMU.

ERR,10- A BITE or system ready failure for IMU 1
ERR,11- A BITE or system ready failure for IMU 2
ERR,12- A BITE or system ready failure for IMU 3

Certain types of errors are indicative of more general system or software problems. If they occur, one of the following messages will be printed and the entire run will be aborted.

ERR,01- The Kalman Filter has failed to converge.
ERR,02- A computed calibration parameter is grossly out of tolerance.
ERR,03- The gross torquing rate test has been failed.

In addition to all the above data, the nominal "down list" of data is sent to the HP-2116B every .2 seconds. (See definition of nominal down list in Appendix B.)

3.6.5 Altering the Succession of IMU Calibrations

As IMUCAL is delivered, IMU #1 is calibrated first, followed automatically by IMU #2, which is followed, with the program terminating, by IMU #3. This sequence can be altered such as to limit calibration to a single IMU, by loading a list of IMU designations into unused memory and loading NEXTPTR (in the program module DLCAL) with the address of this altered list. The present list looks like (with NEXTPTR set to the address of NEXTJ):

NEXTJ (Points to IMU #1)
NEXTJ+1 (Points to IMU #2)
NEXTJ+2 (Points to IMU #3)
NEXTJ+3 (Causes termination of IMUCAL)

At the completion of calibration, an IMU is not left in the (North, West, Up) orientation. Thus, it is presently not possible to successively calibrate the same IMU using this proceedure without manual intervention. It is expected that in the future a termination sequence of slews will be added to the present program, making successive runs possible.

3.7 System Acceptance Tests

The foregoing has been a brief digest of procedures for verifying the laboratory system. When ready, the system will be subjected to acceptance tests of both Tapes 1 and 2 by NASA/MSFC. These tests are described in CSDL Avionics Memo #74-4. Once accepted by NASA, the system will be dedicated to the test plan described in this report.

3.8 Periodic Hardware Recheck

It is reccommended that NASA/MSFC test personnel maintain an accurate and informative hardware status log. Included in the log should be:

(1) Elapsed operating time on all units

(2) A record of system turn-on/turn-offs

(3) Daily records of all analog test points

A daily survey of measurable voltages and currents should be made, particularly verifying outputs of the PDB. In the present IMU design, temperature of the cluster is not monitorable.

If any hardware problems are suspected, isolation is most easily made by using a combination of the tests described in this chapter. Experience with the system will provide a basis for outlining the diagnostic tests required.

4.0 FAILURE DETECTION AND ISOLATION ALGORITHM EVALUATION

Detailed evaluation of failure detection and isolation (FDI) algorithms and their associated redundancy management routines forms the heart of this test program. Establishment of effective approaches to the FDI problem in redundant inertial systems (as for the shuttle vehicle) is a primary goal of this program.

Four FDI algorithms are presented for evaluation. The reader is refered to Volume III of this report, Multiple IMU System Software Design and Coding, for detailed descriptions and flow charts of these programs. Short descriptions are presented here. In a system of three colinear IMUs, FDI can be performed based either on velocity information (VFDI) or attitude information (AFDI). For two skewed IMUs operating, FDI algorithms have been coded based on velocity information (TWOVFDI) and attitude information (TWOAFDI).

With three IMUs in navigation, VFDI is performed every 2s, or AFDI every 200s. Briefly, VFDI (operator sets FDIFLG=1) determines an average $\overline{\Delta V}$, over the two second interval, for the three IMUs. A normalized error velocity component (relative to the average) is determined for each of the nine functional axes. If the normalized sum of the squared components along one navigational axis (the "detection ratios" DRX, DRY, DRZ) exceeds a constant threshold, an error detection is signalled. The ratio of each of those squared components to the sum squared is then compared with a constant threshold as the means of isolation ("isolation ratio"). Detection constants exist both at "3σ" instrument performance and at "redline" or required mission performance levels.

AFDI is exercised every 200s while three IMUs are in navigation (when the operator sets FDIFLG=2). Briefly, rotation vectors are determined for each IMU, and, from them, an average rotation vector. An error rotation vector is derived for each IMU, and its components are processed as are velocity error components in VFDI.

With two skewed IMUs, both FDI algorithms are run conccurrently. TWOVFDI, which is iterated every 2s, compares the measured ΔV of each IMU with that of the other IMU transformed into its own frame. The magnitude of the error velocity is compared with a preset detection threshold. If an error is detected, the largest components of the two error velocity vectors are compared with an isolation threshold.

TWOAFDI, processed every 50s, computes an error rotation vector for each IMU relative to the other, and processes its components in a manner similar to velocity error component processing in TWOVFDI. Detection and isolation thresholds have been preset.

If a first failure is isolated, the higher numbered IMU of the two remaining is skewed relative to the stabilized lower numbered IMU. Skewing is started and monitored by the NAV/FDI scheduler, which also maintains navigation using only data from the stabilized IMU during the slewing. The scheduler then initiates skewed IMU navigation and FDI. A second failure causes the navigator to continue using the data from the single remaining IMU. No FDI algorithm is exercised.

In addition to these FDI algorithms, two hard failure monitors are present in the executive. First, EXEC interrogates each IU's status register. This word includes IMU READY, IMS FAIL and IMU BITE bits. The IMS FAIL bit may be set by a toggle switch on the IU. $\overline{\text{IMU READY}}$, IMS FAIL and IMU BITE will hard fail an IMU and cause it to be disregarded in all calculations. There is also a reasonability test on IMU data. Apparent acceleration greater than 100 m/s^2 (low gain) or 10 m/s^2 (high gain), and gimbal rates greater than 20^{o}s, in the raw data are taken as indicating a hard failure. The NAV/FDI scheduler then initiates the redundancy management scheme described above.

4.1 Proposed Evaluations

It is suggested that the following evaluations be carried out. In each case, the given number of IMUs are navigating on a static table.

(1) Demonstration of response to hard failures is made. Hard failures are engendered both by the IMS FAIL switch and through lowering hard failure thresholds to easily attainable levels. System navigator response is observed. Second failures are caused in a similar fashion, and the response of the redundancy management is again observed. It is intended that the redundancy management's response to hard failures will be proven, and that navigator performance across failure detection and reconfiguration will be shown to be an adequate tool for evaluating response of the FDI algorithms.

(2) VFDI will be exercised through both accelerometer and gyro parameter miscompensations. In each case, comparison of velocity error ratios and resolution times will be made with those presented. Management of the failure will be observed.

(3) AFDI will be exercised similarly, with response to a series of gyro errors observed. Again, test results will be compared with values drawn from simulations.

(4) TWOVFDI and TWOAFDI will be demonstrated in a similar manner, examining response to both accelerometer and gyro errors. Continued navigation with the single remaining IMU will be shown with both the (North, West, Up) and the skewed IMU remaining.

(5) Working with the established FDI algorithms, efforts will be made to show susceptability to other variables: threshold levels, inter-IMU alignment, aritficial noise on various instrument parameters. Where possible, results will be compared with predictions.

Additional tests will be carried out as time and interest dictate. Dynamic tests are possible but are limited by overhead cabling. FDI response with prenavigation filters added to the software could also be examined.

As navigator performance is a major tool in evaluating system response to failures, navigation with no failures should be determined as a baseline. A one hour run should be performed.

4.1.1 Demonstration of Hard Failure Monitors

The two hard failure monitors just described are demonstrated first, with two intended objectives. One, demonstration of the monitors themselves. Two, demonstration of redundancy management of first and second failures. This second objective will provide a principal tool for evaluation of FDI algorithm performance.

4.1.1.1 Response to IMS FAIL Discrete

For this first test, it is not necessary that the platforms be aligned. Rough alignment by self-leveling and slewing azimuth to near zero will suffice.

The three IMUs are placed inertial mode, FDIFLG is set to zero (no FDI algorithm processing) and navigation is started. Sufficient time should be allowed to demonstrate navigation performance before a failure is set.

HEX,7AFO	CR
2700	CR
2700	CR
2700	CR
#	CR
CMD,1,17	CR

CMD,2,17	CR
CMD,3,17	CR
HEX,302A	CR
0	CR
#	CR
SEQ,FDINAV	CR
RUN,	CR

The IMS FAIL discrete is now set at any IU. That IMU string will be failed during the next major cycle. The expected response is that the higher numbered platform of the two remaining will be skewed relative to the lower. Messages will be printed indicating that the appropriate IMU is slewing and that it has reached the skewed position. (A complete table of FDI Error Messages and Codes appears in Appendix D, Table D-3.) In addition to the error messages, FDI and navigation data will be displayed continually at the typewriter. The Typewriter Format, FDI/NAVIGATION is shown as Table B-4. The change in gimbal angles of the slewed platform will be readily apparent. Additionally, Q_{SNS}, representing the transformation from the skewed to the non-skewed platforms, can be sampled. The proper value is:

$$\lambda = 0.5$$
$$\rho_x = 0.0$$
$$\rho_y = 0.30902$$
$$\rho_z = 0.80902$$

representing successive rotations of:

$$\theta_x = 31^\circ\ 43'$$
$$\theta_y = 180^\circ$$
$$\theta_z = 121^\circ\ 43'$$

The system is not responsive to the typewriter while in any of the application programs. Thus, sampling Q_{SNS} can occur only after stopping navigation. Depress the ABORT button on the FOU. Sample the four double precision elements of Q_{SNS} (λ, ρ_x, ρ_y, ρ_z):

EXP,282C	CR	(displays λ)
	CR	(displays ρ_x)
	CR	(displays ρ_y)
	CR	(displays ρ_z)
#	CR	(terminates display)

If navigation is continued with two skewed IMUs on line, a second failure may then be set on either the skewed or non-skewed IMU. The failure will be noted in the appropriate status word. Continuing navigation will be displayed at the typewriter.

This test may be performed for each of the six first/second failure permutations.

4.1.1.2 Response to Hard Data Failures

Data reasonability tests are performed on the raw system output. The limits presented in the delivered tape are: (1) low gain CAPRI data is tested against 2000 integer pulses over a 0.2s period, or 100 m/s^2 (LCHFD, location OA81), (2) high gain CAPRI data is tested against 20000 integer pulses over a 0.2s period, or 10 m/s^2 (HCHFD, location OA82), and (3) gimbal angle data is tested against a change in angle of 0.8° over a 0.04s period, or $20^\circ/s$ (GHFD, location OA83). It is suggested that this monitor is best demonstrated by lowering these thresholds to attainable levels.

Navigation is performed with the CAPRIs in low gain, i.e., NAVFDI sets low gain as part of its initialization procedure. Tests of velocity information hard failures are, therefore, difficult. One might patch out the instruction resetting the scale factor, and then run NAVFDI with IMUs off level.

A test can be made of the gimbal rate hard failure detection quite easily, however.

S/D quatization of 80 $\widehat{sec}$ sets a lower bound on GHFD of 0.44 $^\circ/s$. This value exceeds rates which may be applied to the platforms by GYPTO, but can be attained on any axis by analog slews. The test which is suggested involves lowering the threshold, GHFD (location OA83), starting navigation with three colinear IMUs, failing one by means of the IMS FAIL switch and observing that the IMU being skewed exceeds GHFD and is failed. Error messages (drawn from Table D-3) will be printed indicating the skewing process and this failure. Thus, with three platforms in System Ready and rough aligned:

```
HEX,OA82      CR
     07DO     CR
       #      CR
SEQ,FDINAV    CR
RUN,          CR
```

Anytime after navigation has begun, fail IMU 1 by means of the IMS FAIL switch. IMU 3 will be commanded to skew, and these messages will be displayed:

MSG,EC (IMU 3 starting to skew)
ERR,53 (Gimbal rate hard failure, IMU 3 roll axis).

This test may be repeated for any initial failure. Navigation will continue with one IMU.

4.1.1.3 Observations

In the foregoing tests, procedures for evaluating response to FDI algorithms have been shown. First, monitoring the slewing process by examination of Q_{SNS} has been demonstrated. Second, navigation across first and second failures has been shown.

4.1.2 Demonstration of VFDI

Conditions for processing of VFDI are these: (1) three non-failed IMUs are navigating, and (2) FDIFLG (location 302A) = 1. Hard failure limits are set at delivered values.

VFDI is responsive to both accelerometer and gyro errors, both of which shall be exercised here. Downlink data as listed in Table B-4 includes the detection constants calculated in the last major cycle and the isolation ratio for each of the nine functional axes. FDI messages will be printed as events occur. Reference should be made to Table D-3, FDI messages.

Suggested Demonstrations of VFDI are presented in Table 4-1. These demonstrations are intended to explore resolution of the algorithm with respect to both error detection and isolation. Response time will also be explored, along with navigation errors introduced prior to isolation.

As in previous tests of the hard failure monitors, the isolated platform will be taken offline, and the higher numbered of the two remaining platforms will be torqued to the skew orientation.

Table 4-1. Suggested Demonstrations of VFDI

Summary of thresholds in delivered Tape 1:

Detection Levels (VFDI) in Laboratory Environment

3σ Level: $KD3S_{DR} = 1 \times 10^{-6}$ $(cm/s)^2$ $KD3S_{CR} = 6.25 \times 10^{-6}$ $(cm/s)^2$ $KD3S_{VERT} = 1 \times 10^{-6}$ $(cm/s)^2$	Detection occurs when $V_{ET_j}^{\ 2} > K_j$, j = axis, at both 3σ and redline levels.
Redline Level: $KDRL_{DR} = 3.6 \times 10^{-5}$ $(cm/s)^2$ $KDRL_{CR} = 3.6 \times 10^{-5}$ $(cm/s)^2$ $KDRL_{VERT} = 3.6 \times 10^{-5}$ $(cm/s)^2$	

Isolation Ratio (VFDI) in Laboratory Environment

KIS = 0.59	Isolation occurs when $\frac{V_{ER_{ij}}}{V_{ET_j}} > KIS$, i = IMU, j = axis

Suggested test by alteration of horizontal accelerometer bias:

Single Horizontal Axis Bias BLX_i or BLY_i	Single Axis $V_{ET_j}^{\ 2}$	$\frac{V_{ER}}{V_{ET}}$ bias $\sigma=0.1$ cm/s^2	$\frac{V_{ER}}{V_{ET}}$ bias $\sigma=0.25$ cm/s^2
± 0.1 cm/s^2	10^{-8} (cm/s^2)	0.00	0.00
± 0.3 cm/s^2	10^{-7} (cm/s^2)	0.40	0.05
± 1.0 cm/s^2	10^{-6} (cm/s^2)	0.69	0.43
± 3.0 cm/s^2	10^{-5} (cm/s^2)	0.88	0.73
± 10.0 cm/s^2	10^{-4} (cm/s^2)	0.96	0.91

Table 4-1. Suggested Demonstrations of VFDI (continued)

Suggested test by alteration of vertical accelerometer scale factor:

Single Vertical Axis SF, KLZ (ft/s/pulse)	Single Axis $V_{ET_Z}^{2}$ $(cm/s)^2$	$\left.\frac{V_{ER}}{V_{ET}}\right\vert_{\sigma = 0.1\ cm/s^2}$ bias	$\left.\frac{V_{ER}}{V_{ET}}\right\vert_{\sigma = 0.25\ cm/s^2}$ bias
0.0310400	10^{-3}	0.99	0.97
0.0316800	10^{-4}	0.96	0.91
0.0319040	10^{-5}	0.88	0.73
0.0319680	10^{-6}	0.69	0.43
0.0319904	10^{-7}	0.40	0.05
0.0319968	10^{-8}	0.00	0.00
0.0320000	Nominal	----	----
0.0320032	10^{-8}	0.00	0.00
0.0320096	10^{-7}	0.40	0.05
0.0320320	10^{-6}	0.69	0.43
0.0320960	10^{-5}	0.88	0.73
0.0323200	10^{-4}	0.96	0.91
0.0329600	10^{-3}	0.99	0.97

Suggested test by alteration of horizontal gyro bias:

Single Horizontal Gyro Channel Drift, DXRA or DYRA (^{o}/hr)	Expected Resolution Time (s)*
1.0	2060
3.0	686
10.0	206
20.0	103
30.0	69
40.0	52
50.0	41

* This represents the time required to detect and isolate an apparent bias failure of the complementary level accelerometer, at approximately g sin θ = 6 cm/s^2.

The specific procedure for these tests is:

(1)Alter the specific parameter to be changed, using either the FIX, command at the particular data location or the MISCTAB option. Note: it must be reemphasized that the parameter value entered in the MISCTAB table is a change in the stated parameter, to be added to the loaded value and not to replace it. In addition, the CAPRI bias terms (BLX,BLY,BLZ) are not changed. In tests employing the bias terms, the locations

BLXDT	=	.2 BLX
BLYDT	=	.2 BLY
BLZDT	=	.2 BLZ

(which are tabulated in section 3.4.1) are changed instead. The changes are scaled by 0.2 the value presented in Appendix C. This warning applies only to CAPRI bias terms.

(2)Set FDIFLG = 1

INT, 302A	CR
1	CR
#	CR

(3)Level and align the platforms.

(4)Commence ground alignments,

SEQ, GRDALN	CR
RUN,	CR

4.1.3 Demonstration of AFDI

Conditions for processing of AFDI are these: (1) three non-failed IMUs are navigating, and (2) FDIFLG=2. Hard failures limits should be kept at delivered values.

AFDI is responsive only to gyro errors. That is, no velocity information enters the processing. Downlink data, again conforming to Table B-4, includes detection constants and isolation ratios. Messages employed in AFDI also appear in Table D-3.

Suggested Demonstrations of AFDI are presented in Table 4-2. These demonstrations are intended to explore resolution of the algorithm with respect both to detection and isolation.

Response to a failure isolation, as before, will be skewing of an IMU and introduction of skewed IMU navigation and FDI. Response time and navigation errors prior to isolation will be explored.

Procedure for invoking these tests follows:

(1)Alter the specific parameter to be changed, using either the FIX, command at the particular data location or the MISCTAB option.

(2)Set FDIFLG = 2

INT,302A	CR
2	CR
#	CR

(3)Level and align the platforms.

(4)Commence ground alignment

SEQ,GRDALN	CR
RUN,	CR

4.1.4 Demonstration of TWOVFDI and TWOAFDI

Velocity and attitude information based FDI algoithms are processed concurrently in the skewed configuration. Iteration times are 2s and 50s respectively. Conditions for skewed IMU operation are that one IMU be failed and the other two IMUs be navigating. Hard failure thresholds are left at the same values used for colinerar IMUs.

These FDI algorithms are responsive to both accelerometer errors, both of which will be exercised. Downlink data is shown in Figure B-4, Typewriter Format, TWO IMU FDI/NAVIGATION, and includes latest detection values and isolation unit vectors for both the non-skewed and skewed IMUs. FDI messages associated with these routines appear in Table D-1.

Table 4-2. Suggested Demonstrations of AFDI

Detection Levels (AFDI) in Laboratory Environment

$KDA_j = 1.322 \times 10^{-11}\ (\text{rad/s})^2$ $= 0.560\ (^\circ/\text{hr})^2$	For all axes. Detection occurs when $ATSE_j > KDA_j$

Isolation Ratio (AFDI) in Laboratory Environment

KIS = 0.59	Isolation occurs when $\frac{DRFT_{ij}^2}{ATSE_j} > KIS$, i=IMU, j=axis

Suggested Test by Alteration of Gyro Bias

West axis (y) bias	$ATSE_y$	$\frac{DRFT_{iy}^2}{ATSE_y}$ bias $\sigma = 0.0\ ^\circ/\text{hr}$	$\frac{DRFT_{iy}^2}{ATSE_y}$ bias $\sigma = 0.05^\circ/\text{hr}$	$\frac{DRFT_{iy}^2}{ATSE_y}$ bias $\sigma = 0.1^\circ/\text{hr}$
$\pm 0.1\ ^\circ/\text{hr}$	$0.00\ (^\circ/\text{hr})^2$	0.67	0.00	0.11
$\pm 0.3\ ^\circ/\text{hr}$	$0.06\ (^\circ/\text{hr})^2$	0.67	0.05	0.35
$\pm 1.0\ ^\circ/\text{hr}$	$0.67\ (^\circ/\text{hr})^2$	0.67	0.64	0.46
$\pm 2.0\ ^\circ/\text{hr}$	$2.67\ (^\circ/\text{hr})^2$	0.67	0.66	0.55
$\pm 3.0\ ^\circ/\text{hr}$	$6.00\ (^\circ/\text{hr})^2$	0.67	0.66	0.59

Suggested Demonstrations of Two IMU FDI Algorithms are listed in Table 4-3. It is intended that resolution of each algorithm will be explored, along with resolution time and navigation errors introduced by as yet non-isolated failures.

Second failure isolation, as shown in hard failure monitor evaluations, results in continuing navigation using only the remaining IMU (whether non-skewed or skewed). Two IMU FDI is invoked by:

(1) Failing an IMU (IMU_I) either with its IMS FAIL switch, or by CMD,I,18 CR, setting NEWFAIL (location 302E) = i, and setting FDIFLG (location 302A) = 1,

(2) Altering the specific parameter to be changed, using either the FIX, command or the MISCTAB option,

(3) Rough aligning the two on line platforms, and

(4) Initialing navigation

SEQ,GRDALN CR
RUN, CR

This call will skew the two non-failed IMUs, begin navigation and schedule FDI processing, after gyrocompassing.

4.1.5 End-to-end Tests of FDI

End-to-end tests of the FDINAV algorithms can be demonstrated using the MISCTAB option to control complex series of parameter changes automatically. One suggested test is this: Ground align and gyrocompass three colinear IMUs for one hour. Ten minutes into navigation/FDI initiate a velocity redline failure on the X axis of IMU 3. Twenty minutes later, initiate an attitude failure condition on the Y axis of IMU 2. The initialization procedure is:

1. Manually align the IMUs so that roll axes point North.
2. Power up IMUs. Upon observing "System Ready" lights, individually slew all IMUs in azimuth so that azimuth angles read zero.
3. Place all IMUs on line:

CMD,1,19 CR
CMD,2.19 CR
CMD,3,19 CR

4. Initialize items as follows:

GCTIME	=	360000 cs (Gyrocompass time, in location 305C)
FDIFLG	=	1 (VFDI for 3 colinear IMUs, in location 302A)
MISCTAB+0,+1	=	60000 cs (time for 1st failure)
MISCTAB+2,+3	=	X (value to be added to CAPRI bias BLXDT for X axis of IMU 3, scaled as in Appendix C)

Table 4-3 Suggested Demonstrations of Two IMU FDI Algorithms

Detection and Isolation Levels for Two IMU FDI in Laboratory Environment:

KD2V = 1.50×10^{2} cm/s KD2A = 3.88×10^{-6} rad/s	Detection occurs when magnitude of error vector > KD2X
KI2V = 0.93 KI2A = 0.93	Isolation when maximum component of unit error vector muVE > KI2X

Suggested test by alteration of horizontal accelerometer bias (non-skewed IMU), ideal system except for accelerometer bias:

Acc. Bias	Detection time	muVE $\sigma = 0.1$	muVE $\sigma = 0.2$	muVE $\sigma = 0.3$	muVE $\sigma = 0.5$
$\pm$ 0.1 cm/s^2	1500s	.88	.83	.81	.79
$\pm$ 0.3 cm/s^2	500s	.95	.90	.87	.82
$\pm$ 1.0 cm/s^2	150s	.99	.97	.95	.91
$\pm$ 3.0 cm/s^2	50s	.995	.99	.995	.97
$\pm$ 10.0 cm/s^2	15s	.999	.999	.999	.995

Suggested test by alteration of West axis gyro bias (non-skewed IMU), ideal system except for gyro bias:

Gyro Bias	Detection time	muAE $\sigma = 0.00$	muAE $\sigma = 0.01$	muAE $\sigma = 0.03$
0.03 ^{o}/hr	100s	0.99	0.87	0.64
0.10 ^{o}/hr	25s	0.99	0.93	0.86
0.30 ^{o}/hr	25s	0.99	0.95	0.94
1.00 ^{o}/hr	25s	0.99	0.99	0.99

MISCTAB+4	=	OA90 (address of the BLXDT for IMU 3)
MISCTAB+6,+7	=	180000 cs (time for 2nd failure)
MISCTAB+8,+9	=	Y (value to be added to gyro bias of Y axis gyro on IMU 2, scaled as in APPENDIX C)
MISCTAB+10	=	OA40 (address of DYRA for IMU 2)

5. Start the test:

```
SEQ,GRDALN    CR
RUN,          CR
```

In addition to the ground alignment gyrocompass and navigation data printouts, the following printouts should be observed in FDI/Navigation:

ERR, 1C	-1st failure 3σdetection
ERR, 3D	-1st failure 3σisolation
ERR, 1E	-1st failure redline detection
ERR, 3F	-1st failure readline isolation
MSG, EB	-IMU 2 slewing to skewed configuration
MSG, FB	-IMU 2 in skewed configuration
ERR, 82	-2nd failure (attitude) is detected
ERR, BB	-2nd failure is isolated

Fuller explanation of these messages appears in Appendix D.

It is important that the data avilable in this sequence be examined fully. Navigation data should be consistent with three, two and one IMUs online. Resolution time for the drift failure should be compared with the expected value.

With this tool proven, test sequences may now be defined and programmed at will. MISCTAB permits up to six parameter changes to be preprogrammed.

4.2 Examination of Non-Instrument Parameter Effect

With knowledge of FDI algorithm performance and of the tools for evaluating system response available, attention is turned to examination of the effects of error sources other than inertial instrument errors. It is suggested that the following areas be examined.

(1) Evaluation of FDI degradation due to inter-IMU misalignments is made.

(2) Evaluation is made of the effect on resolution of varying the algorithms' thresholds.

4.2.1 Effect of Inter-IMU Misalignments

A series of tests is made which demonstrates the effect of purposeful misalignment of one IMU to the system. That is, through biasing the gyrocompassing, one IMU is misaligned to the other two. In the skewed configuration, one IMU can be torqued slightly out of alignment.

Resolution of the FDI (as determined in earlier tests) in then examined as alignment degrades. Attitude information based algorithms depend on rate calculations, and will not be effected in a first order way. Velocity information based algorithms will show first order effects.

The procedure for these tests, then, is:

(1) Align the platforms, introducing the desired misalignment

(2) Proceed as in Sections 4.1.2 and 4.1.4.

4.2.2 Evaluation of Threshold Levels

Threshold levels in the delivered software have been drawn from extensive simulations of the multiple IMU system in the shuttle vehicle environment. Studies of the multiple IMU system's FDI algorithms have demonstrated performance dependence on threshold levels. A detailed test program, using the full hardware and actual system real time software, must be used to demonstrate this dependence. Final thresholds for this system will be chosen and demonstrated through tradeoffs considering available resolution, the number of missed detections, and the number of missed and false isolations with respect to proper isolations.

The procedure for these tests follows those already used. Systematic variations in the threshold values are introduced, from the typewriter, in the locations of which are tabulated in Table 4-4, FDI Algorithm Thresholds. These are all floating point, double precision numbers, and are changed using the EXP, command.

4.2.3 Other Variables

Performance of the FDI algorithms is affected by other variables. Systematic variations in the threshold values are introduced. Instrument and gimbal non-orthogon-

Table 4-4. FDI Algorithm Thresholds

Mnemonic	Function	Location	Nominal Value
VFDI			
KD3S + 0	3σ Threshold, X axis	165C	1.0×10^{-6} $(cm/s)^2$
KD3S + 2	3σ Threshold, Y axis	165E	6.3×10^{-6} "
KD3S + 4	3σ Threshold, Z axis	1660	1.0×10^{-6} "
KDRL + 0	Red line threshold, X	1662	3.6×10^{-5} "
KDRL + 2	Red line threshold, Y	1664	3.6×10^{-5} "
KDRL + 4	Red line threshold, Z	1666	3.6×10^{-5} "
KIS	Isolation ratio	1578	0.59 ------
AFDI			
KDA + 0	Detection threshold, X	1656	1.322×10^{-11} $(rad/s)^2$
KDA + 2	Detection threshold, Y	1658	1.322×10^{-11} "
KDA + 4	Detection threshold, Z	165A	1.322×10^{-11} "
KIS	Isolation ratio	1578	0.59 ------
TWOVFDI			
KD2V	Detection threshold	1ED2	1.5×10^{2} cm/s
KI2V	Isolation ratio	1ED4	0.93 ------
TWOAFDI			
KD2A	Detection threshold	1AB8	3.88×10^{-6} rad/s
KI2A	Isolation ratio	1ABA	0.93 ------

alities,as examples, will contribute to the background noise. Instrument noise (due to any cause) will tend to mask degradations. Specific tests of these other variables might be devised utilizing both hardware and software changes. None are presented here.

4.3 Conclusions

The intent of the tests presented in this chapter has been to demonstrate the capabilities of deterministic, collaborative FDI algorithms. This system provides a primary tool for evaluation of automatic soft failure detection and isolation in redundant inertial systems.

These tests have included studies of instrument and non-instrument related error sources. Resolution of the algorithms has been explored in the test series delineated in Tables 4-1, 4-2 and 4-3. Techniques for exploration of non-instrument errors have been suggested.

5.0 GROUND ALIGNMENT AND GYROCOMPASSING ALGORITHM EVALUATION

In the multiple IMU system software, algorithms are designed to align and gyrocompass any subset of the three IMUs to a (North, West, Up) frame simultaneously. It is possible to perform testing of these algorithms to any desired depth, but it is suggested that testing be limited in recognition of the fact that virtually no new technology has been required to extend classical algorithms to the multiple IMU case.

Ground alignment computes bias drifts for the level gyros and coarse alignment in azimuth prior to gyro compassing. At termination of ground alignment the system immediately enters gyrocompass. Verification of ground alignment is based on run-to-run stability of computed bias drifts, as well as the terminal azimuth error.

The gyrocompass is a closed loop algorithm which maintains the platform at level and drives the north velocity to zero. Verification of the program is based primarily on the repeatability of the final platform orientation and stable north velocity level.

5.1 Invoking the Ground Alignment and Gyrocompass Programs

Two major cycle programs are of interest. These are GALGN, the ground alignment program, and GYRCMP, the gyrocompass. Detailed descriptions and flow charts appear in sections 3.1 and 3.2, respectively, of Volume III, Multiple IMU System Software Design and Coding.

Initial requirements for GALGN are that (1) at least one IMU is not failed, (2) that compensation parameters are loaded, (3) that the platform(s) are within 5^{o} of level and (4) within 30^{o} of north pointing. The program itself then carries the system through eleven sequences which serve to estimate X and Y channel bias drifts, level the platforms, and compute the azimuth offset angle.

GYRCMP requires (1) completion of GALGN, and (2) that CAPRI compensation and accumulation has been initiated. It individually forces each IMU toward a stable, level and north pointing attitude.

Operation of these two routines is controlled by the ground alignment/gyrocompass scheduler (GRDAGYRC). Program transfer from GALGN to GYRCMP is automatic.

The following procedure will initiate the ground alignment program.

1. Select those IMUs to be on line for the present run using the CMD,i,18, and CMD,i,19 commands.
2. Power up the system and observe the three "System Ready" lights.
3. Manually align the platforms so that their X axes are approximately north pointing (within 30°).
4. Select and start the ground alignment sequence:

SEQ,GRDALN	CR
RUN,	CR

The total time required for ground alignment is approximately 20 minutes. This may vary because of differences in the time required to correct level and azimuth errors. Ground alignment may be terminated by depressing the ABORT button on the FOU. If no termination is requested, processing will move automatically to gyrocompassing.

Various messages will be printed at the FOU typewriter indicating the start of alignment sequences. These are:

MSG,00	Minus 90° azimuth slew.
MSG,01	Rapid erection of platform.
MSG,02	Rapid erection of platform.
MSG,03	Refinement of platform level. There will be sixteen refinements prior to sequence 4 (that is, "MSG,03" is printed sixteen times) and five more refinements prior to sequence 9 ("MSG,03" printed five times).
MSG,04	Azimuth error measurement.
MSG,05	Azimuth error correction.
MSG,06	Y gyro calibration.
MSG,07	Positive 90° slew.
MSG,08	Relevel and stabilization.
MSG,09	X gyro calibration.
MSG,10	Termination of ground alignment and start of gyrocompass.

Gyrocompassing nominally continues for 45 minutes before automatic transfer to the FDI/NAVIGATION programs. This time (GCTIME, location 305C, an integer number of centiseconds) may be reset before the run. Alternatively, a switch on the PIU can be used to change the major cycle task from gyrocompassing to navigation manually. No messages are displayed by the gyrocompass.

In addition to MSG,i (i=0 to 10), data is displayed at the typewriter or through the downlink. Data lists and formats are shown in Figures B-2 and B-3, Typewriter Format, Ground Alignment Program and Typewriter Format, Gyrocompass Program, respectively.

5.2 Tests of Ground Alignment

Several specific tests of ground alignment are suggested to show that reproduceability of the autobiases is not affected by initial platform orientation (within the limits $\pm 5^{\circ}$ from level, $\pm 30^{\circ}$ from north). Separate tests can be run from near zero, $\pm 10^{\circ}$, $\pm 20^{\circ}$ and $\pm 25^{\circ}$ offsets. It can be shown that alignments reached vary predictably with deliberate miscompensations of pertinent insturment biases. Specifically, for a run made with DXRA and DYRA set to zero, it is anticipated that the autobias values will equal minus the nameplate value for Y and equal the nameplate value for X.

Tests of this sort can be run with any combination of the IMUs. Miscompensations are made using the scaling and addresses presented in Appendix C, and loading the test values using the FIX, command. MISCTAB cannot be employed under GRDAGYRC.

Anticipated stability of the autobias terms is on the order of 0.005 $^{\circ}$/hr. The magnitude of each term should also be comparable to the previous calibration value. The principal measure of the ground alignment program, however, will be system navigation performance, as demonstrated in Chapter 8.

5.3 Evaluation of Gyrocompassing

The Gyrocompass routine is evaluated next, both for single and multiple IMU operation. The gyrocompass scheduler allows progression from the ground align program (fixed azimuth torquing) to a closed loop, north-seeking gyrocompass mode. Since the resolution of the gimbal chain (including S/D converter) is 80 arc seconds, on the order of the expected gyrocompass uncertainties, performance evaluation is based on convergence of the north velocity to zero, and on its stability at that point.

5.3.1 Evaluation of Single IMU Gyrocompassing

Operation is initially limited to a single IMU in order to provide baseline performance data for use in evaluating multiple IMU gyrocompassing.

A single IMU is selected, as above. Specific desired miscompensations or alteration in GCTIME are made. The platform X axis is pointed roughly north and the program initiated:

```
SEQ,GRDALN    CR
RUN,          CR
```

Data is displayed at the typewriter, or via the downlink.

Those tests which are suggested are:

(1) Specific evaluation of convergence characteristics. Data is displayed at the typewriter every two minutes, or is sent to the HP2116B 5 times/s. Either format permits sufficient resolution to exhibit initial transients and stability characteristics (within resolution of the S/D converters).

(2) Stable orientations as a function of component errors. Final orientation is a direct function of uncompensated inertial component errors. Systematic variation in, for example, east axis drift must be evaluated.

(3) Response to initial conditions. Initial conditions are determined by the ground alignment program. Initial azimuth offset remains as a variable whose effect on GYRCMP must be explored.

(4) Steady state north velocity. Steady state velocity errors will result if any of several errors are present. Records of north velocity vs. miscompensations should be examined to determine whether systematic errors are present.

5.3.2 Evaluation of Multiple IMU Gyrocompassing

With three IMUs operating simultaneously, the same gyrocompassing data is available as was presented in single IMU testing. The HP2116B interface can handle a 40 KHz word transfer rate. The same tests outlined in Section 5.3.1 (individual IMU gyrocompassing) will be performed with all three IMUs checked simultaneously in the gyrocompass mode. These results will establish effects of noise/cross talk as a function of both single IMU and multiple IMU operation. If discrepancies between single and multiple IMU gyrocompassing are observed, it may then be necessary to run tests using different sets of IMUs to track down the error sources.

Evaluation of the multiple IMU gyrocompass follows those tests described in Section 5.3.1. Tests are initiated in an identical manner, except that either two or three IMUs must be enabled (non-failed).

5.4 Conclusions

The tests described above are intended to demonstrate soundeness of the alignment and gyrocompass algorithms delivered with this system. The most exacting test of these routines remains the subsequent navigation performance. Evaluation of navigator sensitivity to initial misalignments is derived and tested in Chapter 8.

6.0 EVALUATION OF IMU PERFORMANCE DURING GIMBAL FLIP

Two questions arise in consideration of gimbal flip. First, how well is attitude reference maintained across flip? Second, is accurate attitude information available during flip? Each of these questions must be explored before committing a four gimbal platform to the shuttle vehicle.

The present KT-70 IMUs may not be identical with the shuttle IMUs; major changes are being considered for the gimbal servo loops and the attitude chain. There is, however, some utility in reviewing these areas as part of this test plan.

6.1 Introduction

For the KT-70 IMU, the gimbal flip phenomenon will occur as the inner and the outer roll gimbal axes approach perpendicularity; this will occur for pitch maneuvers of approximately 90 degrees with respect to the reference orientation of the IMU. Figure 6-1, Test Table and KT-70 IMU Shown in Reference Position, shows the gimbal axes' alignment in the initial reference position. As the $+/-90^{\circ}$ pitch angle is traversed, it is necessary for the outer roll axis (which is slaved to the inner roll) to rotate (or flip) 180 degrees in order to null the inner roll-outer roll servoloop. The main concerns are the possible loss of accurate inertial reference with the introduction of subsequent navigation errors and the accuracy (and therefore availability for system usage) of the attitude readouts during the duration of flip. Previous testing has indicated that, for perfect pitch maneuvers (within a one arc-minute band), loss of inertial reference will occur even for very low pitch axis rates. At pitch axis rates greater than $30^{\circ}/s$, the shuttle design rate, the loss of inertial reference was found to occur in an even wider angular band with respect to a perfect pitch maneuver. Figure 6-2, KT-70 IMU Gimbal Flip Test Data, shows NASA/JSC test results[1]. In addition to the investigation of inertial reference loss, the attitude accuracy question will also be addressed here and evaluated with the system configuration.

6.2 Test Setup and Procedure

The test is started with the IMU in the reference position (Figure 6-1) achieved by gyrocompassing or by manually zeroing the gimbal angles. The IMUs are placed in the navigation mode, and the test is begun. For the gimbal-flip tests outlined, it is required that the table trunnion axis be driven at a reasonably constant rate through an angle of approximately 92 degrees. As an automatic trunnion-axis drive is not available, a manual drive must be used in order to obtain some degree of control for performance evaluation across gimbal flip.

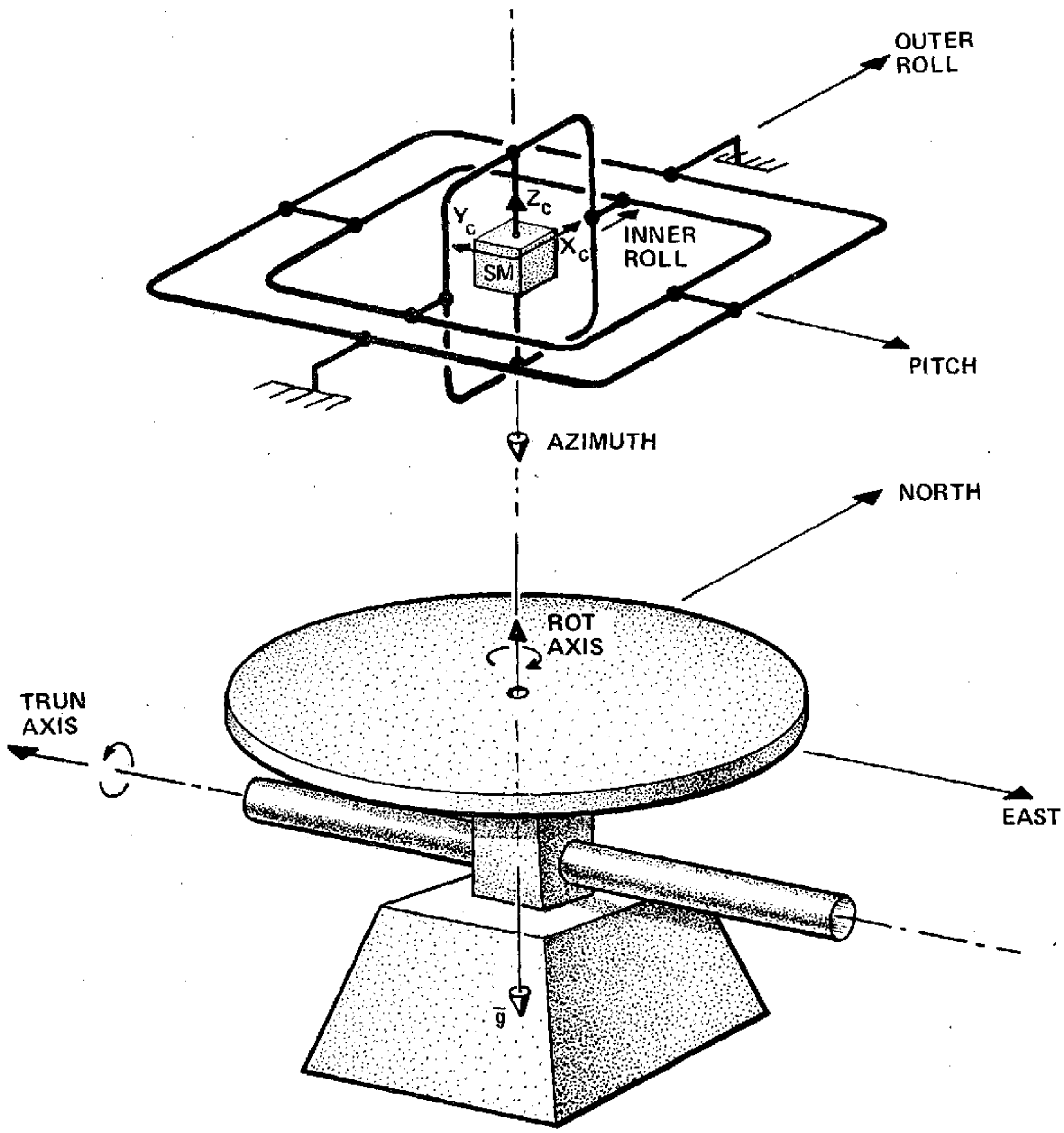


Figure 6-1. Test Table and KT-70 IMU Shown in Ref. Position.

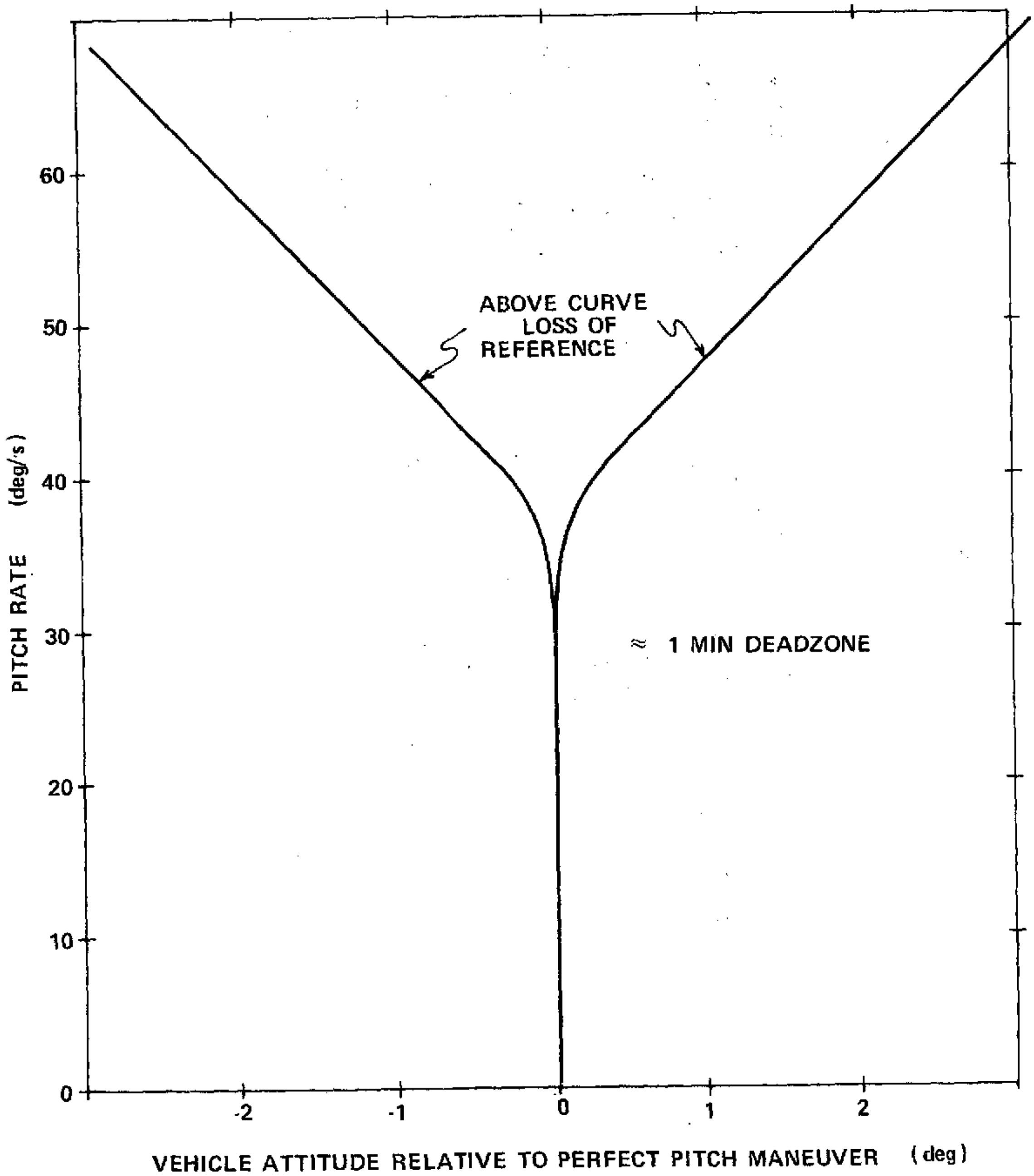


Figure 6-2. KT-70 Inertial Navigation System Gimbal Flip Test.

Table 6-1, Suggested Sequences for Gimbal-Flip Evaluation, lists several proposed test sequences. (Only rates which are practical in a manually driven system are listed. Higher rates would be preferable.)

6.3 IMU Operational Modes During Gimbal Flip Tests

Data rates, particularly in scanning analog test points, preclude testing more than one IMU at a time. The one IMU chosen should be aligned and navigating. (With the other IMUs failed, navigation data will reflect the single unit's ability to hold reference. It is not possible, under existing code, to record gimbal angles and CAPRI data of failed units. However, "before and after" readings may be taken to aid in analyzing flip data.

Both analog and digital monitoring is required during the tests. The digital data includes the navigation parameters, gimbal angles and CAPRI pulses. The analog data is in the form of demodulated ac error signals which indicate the integrity of the gimbal servo loops. The analog signals should be monitored on strip-chart recorders with chart speeds adjusted such that transients occuring during flip are sufficiently displayed for both real-time and post-test analysis. The digital data are outputted from the 4π-CP2 to the HP2116B at a 5 Hz rate. Figure B-4 shows the data format of the digital signals.

Use of the 4π-CP2 and the typewriter interface are outlined in Chapter 3, Volume IV of this report. The following signals will be monitored during the tests.

1. Digital Signals
   - X - Gimbal angles for IMU 1, 2, 3
   - Y - Gimbal angles for IMU 1, 2, 3
   - Z - Gimbal angles for IMU 1, 2, 3
   - X - CAPRIs for IMU 1, 2, 3
   - Y - CAPRIs for IMU 1, 2, 3
   - Z - CAPRIs for IMU 1, 2, 3
   - IMU status words for IMU 1, 2, 3
2. Analog Signals
   - Azimuth Axis post amplifier
   - Inner Roll Axis post amplifier
   - Outer Roll Axis post amplifier
   - Pitch Axis post amplifier
   - Azimuth axis demodulator
   - Pitch axis demodulator

Table 6-1. Suggested Sequences for Gimbal Flip Evaluation

Test Number	Trunnion Axis Slew Rate (^{o}/s)	Total Trunnion Axis Angle (^{o})	Platform Azimuth Offset (^{o})	LOR* Expected
1	1	90+	-1.0	No
2	5		-1.0	
3	10		-1.0	
4	1		-0.5	
5	5		-0.5	
6	10		-0.5	
7	1		-0.1	
8	5		-0.1	
9	10		-0.1	
10	1		-0.01	Yes
11	5		-0.01	
12	10		-0.01	
13	1		+0.01	
14	5		+0.01	
15	10		+0.01	
16	1		+0.1	No
17	5		+0.1	
18	10		+0.1	
19	1		+0.5	
20	5		+0.5	
21	10		+0.5	
22	1		+1.0	
23	5		+1.0	
24	10		+1.0	

*LOR = Loss of Reference

Inner roll axis demodulator
Outer roll axis demodulator

3. <u>Navigation Parameters</u>
   Latitude
   Longitude
   Altitude
   North Velocity
   East Velocity
   Radial Velocity

Note that the analog inner roll axis signals are the only measure of the redundant gimbal angle available in this system.

6.4 Data Reduction and Analysis

The basic mechanism for analyzing the effect of gimbal flip involves one or more of the following:

1. Observation of stable platform inertial reference degradation across flip: this implies that one or more gimbal torquer servos reached saturation and a permanent offset has occured.

2. Monitoring the pickoff between the inner-roll and pitch gimbal (inner roll demodulator): the magnitude of the inner roll excursion from null indicates the magnitude of the azimuth gimbal offset during flip.

3. Monitoring navigation performance: both latitide and longitude errors exhibit increased Schuler amplitudes if platform misalignments are incurred as a result of gimbal flip.

Sequences suggested in Table 6-1 are labelled to indicate those which are expected to result in loss of reference.

6.5 Anticipated Results

With regard to loss of attitude information during flip, any of the suggested tests will provide data. The important parameter to monitor during test sequences is the inner roll demodulator. Angular offsets from null, during flip, could introduce transient errors; that is, the outer roll synchro could indicate false platform attitude about the roll axis, up to the limits of the pickoff stops (± 15 degrees). Monitoring of the inner roll demodulator appears to be the only method of observing this transient effect.

Loss of reference, if it can be caused during these tests, will be manifested by platform misalignments across flip. This can be ascertained by the following:

1) Inner-roll demodulator saturation
2) Subsequent navigation errors with respect to pre-flip navigation tests.
3) Attitude errors as indicated, by transforming the 3-Synchro angles to platform coordinates.
4) Changes in the X, Y and Z accelerometer CAPRI pulse rates can be transformed directly to platform misalignments.

7.0 MULTIPLE IMU CALIBRATION PROGRAM EVALUATION

Tape 2 comprises a KT-70 IMU/4π-CP2 computer calibration program written by Sperry Space Support Division and the executive program (EXEC) designed at CSDL. EXEC, among its other functions, transforms the I/O functions of the Sperry CAL program to render them compatible with the multiple IMU hardware, and permits sequential calibration of up to three IMUs.

The multi-sequence calbration program, which is fully documented in Volume III, Section 3.5, determines nineteen instrument parameters, listing both the previous load (or estimate) and the values it determines. Parameters are listed scaled as in Appendix C.

Testing of the calibration program will involve work in these areas: sensitivity of parameter estimates to table orientation (or, gimbal angles for a given platform orientation), and short and long term parameter stabilities. Calibration of the attitude chain will be examined.

7.1 Altering the Sequence of Calibrations

As IMUCAL (Tape 2) is delivered, IMU #1 is calibrated first, followed sequentially by IMUs #2 and 3. The sequence can be altered, by the method described in Section 3.6.5, to change the order or to limit a run to a single calibration. Note that the delivered version does not permit automatic repeated tests of one IMU, as the program does not leave the tested platform in the (North, West, Up) position. Manual intervention would be necessary to reorient the platform for an additional run.

7.2 Short and Long Term Parameter Stabilities

It is suggested that the calibration program be used to determine short and long term parameter stabilities. Calibrations should be performed as often as is possible, with due regard to other system test requirements.

Short term parameter stability, in the system configuration, is to be evaluated by repetitive testing of a single IMU. That is, the sequence of tests is altered (as described in Section 3.6.5) to command calibration of a single IMU followed by termination. The platform is reoriented and the program run again.

Long term stability testing is accomplished by periodic calibrations of each IMU, with the data subjected to analysis to yield statistical data.

7.3 Calibration Sensitivity to Table Orientation

Ten automatic IMU sequences allow determination of the change in the previously calculated (and stored) gyro bias drifts required to level and align the platform. The calculated bias changes result not only from the actual gyro bias shifts, but are also a function of accelerometer bias shift. Normal ground calibration should be run sequentially in a test series to establish day to day repeatibility.

KT-70 tests have shown gyro bias estimates shifting as a function of IMU case orientation (hence, gimbal relationships). The greatest part of these sensitivities is due to the mass unbalance or g-sensitive terms. Gyro biases measured in these tests, with mass unbalance terms compensated, should not show the variations previously described. It is necessary that attitude sensitivity tests be performed on each of the three IMUs. The suggested orientations are as follows:

1. Table level and the case FORE axis north (the IMU's standard position).
2. Table level and the FORE axis misaligned from north by $\pm 30^{\circ}$. The platform must be aligned to north before calibration is started.
3. Table pitched $\pm 30^{\circ}$ with the FORE axis north. The platform must be leveled before calibration is started.
4. Large azimuth offsets, such as $\pm 45^{\circ}$, $\pm 90^{\circ}$ as time permits.

7.4 Calibration of the Attitude Chain

With a precise calibration of the system instruments available, gimbal chain calibration is performed. Two basic methods can be implemented.

The first method utilizes the calibrated table rotary and trunnion axes to input known angles about the gimbal axes while the platform is maintained in an inertial mode. S/D readings are recorded using the MONITR routine, along with CAPRI readings. Table angles are recorded at the HP2116B. Data reduction entails determining gimbal angles from the accelerometer outputs and comparing them with the laboratory-to-platform transformation determined from measured table and gimbal angles. Compensated CAPRI data may be considered error free for this analysis.

The second approach to calibrating the attitude chain requires recording S/D readings and CAPRI outputs (at 25Hz) while the platform is being slewed 360°. Each axis is slewed individually. Earth rate contributions may be ignored if the slew axis is near east, but will be a maximum of 4 $\widehat{\text{min}}$. Synchro accuracy is presently specified at 6 $\widehat{\text{min}}$.

These tests are performed periodically in order to establish stability of the attitude train. No compensation for attitude indication errors is made in the present system.

7.5 Conclusions

These tests have been outlined to provide a basis for continuing stability tests of the KT-70s, and to provide precise compensation values for the system. Attitude chain tests are not critical as the shuttle version of the IMU will carry an attitude chain which differs significantly.

8.0 INERTIAL NAVIGATOR EVALUATIONS

Following gimbal chain and mass unbalance term calibration, fine grain analysis of inertial navigator performance may be undertaken. The navigation software allows evaluation of both individual IMU and multiple system performance data based on any subset of the IMUs on-line. Whether one, two or three IMUs are on-line, only one set of navigation parameters is calculated, based on an average ΔV. The attitude and accelerometer data from each IMU, however, is available. Figures B-4 and B-5 show the data lists available in colinear (1 or 3 IMU) and skewed (2 IMU) navigation.

Evaluation of the navigator will include these tests: single static IMU navigation, two and three static IMU navigation, and navigation of the system in a dynamic environment.

8.1 Single IMU Navigation

The navigator is first evaluated using a single, compensated IMU in a static test. The two IMUs not being tested are failed, using either the IMS FAIL switch or the CMD,i,18 command. The IMU is sequenced through ground alignment and gyrocompassing, and navigation is entered automatically. With the IMU in system ready,

```
SEQ,GRDALN    CR
RUN,          CR
```

Data, as listed in Figure B-4, will be sent to the HP2116B five times/second.

8.1.1 Baseline Runs

Baseline navigation runs of at least 84 minutes (the Schuler period) will be performed for each IMU. System performance figures of merit will be elements of the system error state vector: latitude, longitude, and north and east velocities. Time characteristics of the errors will also be noted.

8.1.2 Miscompensated Systems

The IMU may be miscompensated either prior to a run, which will effect the initial alignment, or at any time during a run (using the MISCTAB option). This test series is to be used in verifying reaction of the navigator to known errors, and comparison of navigation errors with theoretical estimates.

It must be borne in mind that, with a single IMU on-line, FDI is disabled and errors which FDI would normally flag out will be allowed to propagate. Large compensation errors leading to highly visible navigation errors will, therefore, be useful. Short term characteristics of instrument errors in a pure inertial land navigator appear in Table 8-1, Numerical Values of Error Sensitivities, Single IMU Navigator.

Data for a single IMU system will reflect multiple IMU navigation performance; the navigator employed in this system operates on the average velocity of the n operational units. Errors observed in multiple IMU runs are attenuated by averaging; they are also limited by FDI.

Suggested single IMU tests are presented in Table 8-2, Proposed Tests of a Single IMU Navigator. These errors must, of course, be scaled as in Appendix C.

Maximum compensation ranges (which are available for miscompensation) are:

accelerometer bias	$0.41\ ft/s^2$
gyro drift	$6.29^{\circ}/hr$

Misalignment errors (as shown in Table 8-2) are introduced through accelerometer miscompensations prior to alignment. The MISCTAB option is used to remove the error at transition to navigation so that bias errors do not mask the effects due to initial offsets.

8.1.3 Summary of One IMU Navigation Tests

The intention of this test series is to establish navigator performance. That is, (1) establish the navigation capability of the nominal system, (2) demonstrate that navigator response to errors in the system corresponds to theoretical conclusions, and (3) provide a basis for study of multiple IMU system navigation.

8.2 Navigation With Three Colinear IMUs

The navigator averages velocity information after it has been screened by FDI, and employs the average ΔV in a single integrator and gravity computer. Tests of the full, three IMU system will be similar to those conducted with a single IMU. It will be demonstrated, for example, that the effect of a given instrument error is attenuated by the averaging process.

Table 8-1 Numerical Values of Short Term Error Sensitivities, Single IMU Navigator

Numerical values of short term error sensitivities are tabulated here, with a brief characterization of each term. Evaluation is made for NASA/MSFC's latitude, L = 34.65°. E_N, E_E and E_D are system misalignments about North, East and Down. δL is latitude error. $\delta \ell$ is longitude error. δV_N and δV_E are system velocity errors. ϕ_N and ϕ_E are initial platform misalignments.

Attitude Errors

Error Term	E_N	E_E	E_D
DXRA	Schuler sinusoid, amplitude - 3.99 mrad/°/hr	No effect	Ramp with Schuler sinusoid superimposed slope = 3.22×10^{-3} mrad/s/°/hr amplitude = 2.66 mrad/°/hr
DYRA	No effect	Ramp with Schuler sinusoid superimposed slope = 0.1 mrad/s/°/hr amplitude = 3.99 mrad/°/hr	No effect
DZRA	No effect	No effect	Ramp slope = 4.78×10^{-3} mrad/s/°/hr
BLX	No effect	Schuler sinusoid amplitude = 61 mrad/ft/s^2	No effect
BLY	Schuler sinusoid amplitude = 61 mrad/ft/s^2	No effect	Schuler sinusoid amplitude = 42.7 mrad/ft/s^2
ϕ_N	Schuler sinusoid amplitude = 2 mrad/mrad	No effect	No effect
ϕ_E	No effect	Schuler sinusoid amplitude = 2 mrad/mrad	No effect

Table 8-1, continued

	Velocity Errors		Position Errors	
Error Term	δV_N	δV_E	δL	$\delta \ell$
DXRA	No effect	Schuler sinusoid amplitude = 79.1 $m/s/^{o}/hr$	No effect	Ramp with Schuler sinusoid superimposed, slope = 72.5 $nmi/hr/^{o}/hr$
DYRA	Schuler sinusoid amplitude = 31.3 $m/s/^{o}/hr$	No effect	Ramp with Schuler sinusoid superimposed, slope = 59.8 $nmi/hr/^{o}/hr$ amplitude = 13.3 $nmi/^{o}/hr$	No effect
DZRA	No effect	No effect	No effect	No effect
BLX	Schuler sinusoid amplitude = 256 $m/s/ft/s^2$	No effect	Schuler sinusoid amplitude = 213 $nmi/ft/s^2$	No effect
BLY	No effect	Schuler sinusoid amplitude = 311 $m/s/ft/s^2$	No effect	Schuler sinusoid amplitude = 253 $nmi/ft/s^2$
BLZ	No effect	No effect	No effect	No effect
ϕ_N	No effect	Schuler sinusoid amplitude = 10 m/s/mrad	No effect	Schuler sinusoid amplitude = 8.3 nmi/mrad
ϕ_E	Schuler sinusoid amplitude = 8.6 m/s/mrad	No effect	Schuler sinusoid amplitude = 6.9 nmi/mrad	No effect

Table 8-2. Proposed Tests of a Single IMU Navigator

Error Term	Magnitude	Expected Errors (sensitivities shown in Table 8-1)
None	-	Nominal performance
DXRA	0.03 °/hr 0.10 °/hr 0.30 °/hr 1.00 °/hr	Attitude: Schuler sinusoid about North, ramp with superimposed sinusoid about Down Velocity: Schuler sinusoid on East velocity Position: Ramp with superimposed sinusoid on longitude
DYRA	0.30 °/hr 0.10 °/hr 0.30 °/hr 1.00 °/hr	Attitude: Ramp with superimposed sinusoid about East Velocity: Schuler sinusoid on North velocity Position: Ramp with superimposed sinusoid on latitude
DZRA	0.03 °/hr 0.10 °/hr 0.30 °/hr 1.00 °/hr	Attitude: Ramp about Down Velocity & Position: No effect
BLX	0.01 ft/s^2 0.03 ft/s^2 0.10 ft/s^2 0.30 ft/s^2	Attitude: Schuler sinusoid about East Velocity: Schuler sinusoid on North velocity Position: Schuler sinusoid on latitude
BLY	0.01 ft/s^2 0.03 ft/s^2 0.10 ft/s^2 0.30 ft/s^2	Attitude: Schuler sinusoids about North and Down Velocity: Schuler sinusoid on East velocity Position: Schuler sinusoid on longitude
BLZ	-	No effect expected (contributes only to altitude, which is damped externally)
ϕ_N	1 mrad 2 mrad	Attitude: Schuler sinusoid about North Velocity: Schuler sinusoid on East velocity Position: Schuler sinusoid on longitude
ϕ_E	1 mrad 2 mrad	Attitude: Schuler sinusoid about East Velocity: Schuler sinusoid on North velocity Position: Schuler sinusoid on latitude

8.2.1 Baseline Runs

A series of baseline runs will be made with the full IMU complement. All IMUs are placed on line using the CMD,i,19 command. Navigation is entered, as above, via a call to the ground alignment program.

SEQ,GRDALN	CR
RUN,	CR

As with the single IMU navigator, figures of merit will be the errors in latitude, longitude, and north and east velocities.

8.2.2 Miscompensated Systems

Testing of the three IMU configuration's navigator will be a shortened version of the tests proposed in Section 8.1.2. It might be shown, as one example, that a large single instrument error is attenuated by averaging. Performance characteristics will be similar, but with smaller magnitude. That error in all IMUs will, however, result in error magnitudes similar to those seen in the single IMU case.

8.2.3 Platform-to-Platform Misalignment

One additional error source appears in redundant systems: platform-to-platform misalignment. Initial misalignment of a single platform can be achieved as described in Section 8.1.2. The effect of this error will be, initially, that of a markedly different ΔV measurement's being averaged into the system. Long term effects may be characterized by thinking of that IMU's measured gravity vector's rotating in a different inertial plane. Navigation performance (in short tests), will approximate single IMU navigator performance with initial misalignment.

8.2.4 Summary of Three Colinear IMU Navigation Tests

This test series is intended to show that the delivered navigator's performance is not dependent on the number of IMUs on line.

8.3 Navigation With Two Skewed IMUs

With two skewed IMUs on-line, velocity information from the skewed (higher numbered) platform is transformed into the reference frame. The two ΔV vectors available are then averaged for use by the navigator. Single instrument errors (such as accelerometer bias) in the skewed platform are propagated on all navigation axes because of the skew geometry. Similar errors in the reference platform are propagated on only one axis.

8.3.1 Baseline Runs

Testing of two IMU navigation may take the same form as testing of the three IMU system. One IMU is failed, at any time. Skewing will be caused at the time the navigator senses that only two IMUs are unfailed. Baseline data is expected to show greater dispersion than in previous cases, as the navigator will first be affected by g-sensitive gyro drifts on the X and Y axes (in the skewed IMU). Evaluation again is based upon the figures of merit listed above.

8.3.2 Miscompensated Systems

Studies of the skewed system will follow those procedures described above.

8.3.3 Summary of Two Skewed IMU Navigation Tests

This test series is intended to show that navigator performance is commensurate at all IMU levels.

8.4 Navigator Performance Across IMU Failures

The system navigator is designed to operate with no performance loss across IMU failure and system reconfiguration. A test series is proposed with navigation initiated at the three IMU level, and continued through sequential failures down to the single IMU level.

It must be remembered that FDI is operating whenever more than one IMU is present and FDINAV is running. Thus, large errors introduced by MISCTAB could be used to fail IMUs. Navigation errors caused by this process, however would mask navigator response which is to be demonstrated. Failures, therefore, should be caused by use of the IMS FAIL switch on the IU.

8.4.1 Baseline Runs

With three colinear IMUs on-line and navigating, monitor performance for forty-five minutes. Without otherwise interupting the system, fail an IMU. Observe the skewing process (as described in Chapter Four, and by system messages which are tabulated in Table D-3). Continue navigation for forty-five minutes. Fail either of the remaining IMUs (reference or skewed), observing FDI messages. Observe continuing navigator performance.

These runs will demonstrate continuing navigation in error-free failure situations.

8.4.2 Miscompensated Systems

Similar runs are now made in which large errors are introduced by use of MISCTAB, and FDI decisions cause failure of given IMUs. Navigator performance will be driven by the errors introduced, from the time they are introduced until FDI fails the IMU they are corrupting. Navigator errors, over this period, will be equivalent to those demonstrated above.

8.4.3 Summary

This test series is designed to establish continuing navigation across failures. It is anticipated that performance will be commensurate with that experienced in each individual configuration as shown in previous sections.

8.5 Conclusions

Testing of the inertial land navigator developed for the redundant IMU system has been laid out with three goals in mind.

(1) Demonstration of its performance, in all system configurations.

(2) Demonstration of error propogation, including comparison with theoretical results.

(3) Demonstration of navigation through system reconfiguration.

9.0 TEST PLAN OVERVIEW

The purpose of the multiple IMU system test plan has been to establish the practicality of redundant gimballed IMU systems.

To meet this purpose, given the hardware implementation, it has been necessary to establish the ability to perform failure isolation and detection in all system configurations. Further, the ability to reconfigure also was needed. The tests described in Chapter 4 have been designed to this end.

One other requirement exists: system capability to navigate (and, by inference, perform guidance and control functions) through reconfiguration. This capability has been shown through the tests outlined in Chapter 8.

Other aspects of INS software coded for this system do not represent new technology. Instead, they involve the application of classical work to a new system. Ground alignment, gyrocompassing and calibration programs delivered as part of the redundant IMU system have been adapted from equation sets provided by the IMU's manufacturer. Testing, as outlined in this volume, has served primarily to ensure that navigation and FDI are carried out in a controlled situation.

It is believed that, with the completion of this test plan, a demonstration of the practicality of redundant system design has been shown.

APPENDIX A

ANALOG TEST POINT LISTING

Redundant IMU system signals available to the SSCMS for automatic monitoring are listed and described in this appendix.

55- 46700
AVIONICS MEMO #74-3
ISS MEMO #74-12

To: R. McKern
From: M. Landey
Date: 22 January 1974
Subject: Analog Test Point Listing for the Laboratory Demonstration Multiple IMU System (Revised)

The laboratory demonstration multiple IMU system is monitored by NASA/MSFC's SSCMS equipment. Analog signals from each of the IMUs are carried through test table mounted connectors and slip rings to a patch board at the test station. Each signal will be sampled and recorded when the HP 2116B is commanded to do so, presumably before and after each test run.

This memorandum lists signals available at the patchboard, first grouped by IMU and then by patch panel pin assignments. A suggested scan order is presented.

Cable Monitors

The cable monitor loop designed by Kearfott normally is connected directly to the flight computer. It then serves as a go/no-go check of system readiness. In this system the cable monitor for each string is carried through to the SSCMS patchboard. The resistance across each IMU's pair is measured. Resistance greater than 5Ω indicates a faulty connection.

IMU #1 EL036019 X44 to EL03H022 X43
IMU #2 EL06F041 U38 to EL06F043 U39
IMU #3 EL29X116 T37 to EL30X118 T35

DC Voltage Levels

The following DC voltages are carried out to the SSCMS for each IMU:

Excitation Amplifier	+15.2	±0.150	VDC
" "	-15.2	±0.150	VDC
Platform Voltage	+16	±0.950	VDC
" "	-16	±0.950	"
" "	+15	±0.045	"
" "	-15	±0.045	"
" "	+5	±0.050	"

All DC voltages are to be measured with respect to Platform DC Low. Measurements by the digital voltmeter are considered accurate to +1m VDC. It should noted that these voltages are not adjustable. No measurement of AC ripple is required.

AC Power Signals

The following AC power signals are carried out to the SSCMS for each IMU:

AC power test point 5.0 ±0.2 VAC PHI X
AC power test return Neutral

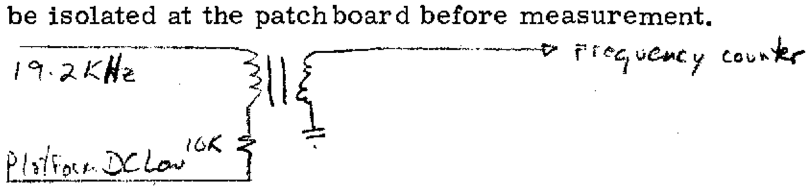
Measurement is made from 5VAC PHI X to Neutral, accurate to 1m VAC. This signal will also be sampled for DC level, which should be 0 ± 0.1VDC.

Gyro Wheel Supply 0° 480 Hz square wave, 32V
Gyro Wheel Supply 90° 480 Hz square wave, 32V

The gyro wheel supply signals are tested both for amplitude of the square wave, 32± 0.5V, and for AC ripple on that signal. AC ripple shall be less than 0.5 VAC. Measurements are made with respect to platform DC Low.

Clock Monitor 19.20±0.02 Khz

The clock monitor is sampled for frequency. It is required that this signal be isolated at the patchboard before measurement.



Inertial Component Monitoring Signals

Five inertial component monitoring signals are available:

X Accelerometer Loop Coarse Level	0 ± 0.5 VDC off; 5 ± 1VDC on
Y Accelerometer Loop Coarse Level	0 ± 0.5 VDC off; 5 ± 1VDC on
Z Accelerometer Loop BITE Test	$0+0.5$ VDC off; 5 ± 1VDC on
X Gyro Axis Analog Torquer Input	0 VDC off; ±7VDC on
Y Gyro Axis Analog Torquer Input	0 VDC off; $+7$VDC on

During vertical erection (61.4 to 122.9 sec. first erection, or during grid mode, magnetic slave, computer fail, or not computer control) the coarse level line allows access to accelerometer analog loops for: 1) monitoring purposes, and 2) controlled slewing of pitch and inner roll axes (coarse level). After this time, these lines carry X and Y accelerometer BITE status. For the Z accelerometer, BITE status is brought out to the patch panel. Horizontal gyroscope axis analog torquer lines are available for monitoring slew commands. Each of these signals is measured with respect to Platform DC Low.

Attitude Chain Test Points

The amplifier output and demodulated signal from three of the four gimbal loops are available. These signals are also measured with respect to Platform DC Low. Wiring to monitor the two outer roll servo loop signals are in place, but has not been connected at IP 1-40 and -42. Pitch, inner roll and azimuth loop signals are available at the patch panel.

Table A-1a. IMU #1 SIGNAL LIST.

SIGNAL		PATCH BOARD POINT	
Excitation Amplifier	+15.2 VDC	EL03J025	X41
" "	-15.2 VDC	EL03K028	X40
Platform Voltage	+16 VDC	EL04A009	N43
" "	-16 VDC	EL04A011	N44
" "	+15 VDC	EL06A044	P43
" "	-15 VDC	EL06A046	P42
" "	+ 5 VDC	EL04B012	Q36
Platform DC Low		EL04B014	Q37
AC Power Test Point 5VAC PHIX		EL01D058	N40
AC Power Test Point 5VAC Neutral		EL01D060	N41
Clock Monitor 19.2 KHz		EL02X002	V37
Gyro Wheel Supply 0^{o} 480 Hz Sq. Wave		EL01C053	Q33
Gyro Wheel Supply 90^{o} 480 Hz Sq. Wave		EL01C055	Q34
X Accelerometer Coarse Level		EL03L061	S40
Y Accelerometer Coarse		EL03L063	S41
Z Accelerometer BITE		EL12A088	V11
X Gyro Analog Torquer Input		EL09A105	P10
Y Gyro Analog Torquer Input		EL09A110	W33
Azimuth Axis Post-Amp.		EL08X081	V35
Inner Roll Axis Post-Amp.		EL07X007	V31
Pitch Axis Post-Amp.		EL05X005	V32
Outer Roll Axis Post-Amp.		EL13B099	T09#
Azimuth Axis Demod.		EL12A089	V10
Inner Roll Axis Demod.		EL12A090	V09
Pitch Axis Demod.		EL12A091	V08
Outer Roll Axis Demod.		EL13A098	T08#

#OR signal lines not connected at IP1

Table A-lb. IMU #2 SIGNAL LIST.

SIGNAL		PATCH BOARD POINT	
Excitation Amplifier	+15.2 VDC	EL06D027	P34
" "	-15.2 VDC	EL06D029	P33
Platform Voltage	+16 VDC	EL06C024	P37
" "	-16 VDC	EL06C026	P36
" "	+15 VDC	EL03A066	W36
" "	-15 VDC	EL03B068	W37
" "	+ 5 VDC	EL06B015	P40
Platform DC Low		EL06B017	P39
AC Power Test Point 5VAC PHIX		EL03E013	W42
AC Power Test Point 5VAC Neutral		EL03F016	W43
Clock Monitor 19.2 KHz		EL13D101	T11
Gyro Wheel Supply 0^{o} 480 Hz Sq. Wave		EL03C070	W39
Gyro Wheel Supply 90^{o} 480 Hz Sq. Wave		EL03D062	W40
X Accelerometer Coarse Level		EL06E030	Q31
Y Accelerometer Coarse Level		EL06E032	P31
Z Accelerometer BITE		EL13C100	T10
X Gyro Analog Torquer Input		EL14J084	Z41
Y Gyro Analog Torquer Input		EL16X069	Z33
Azimuth Axis Post-Amp.		EL20X073	V34
Inner Roll Axis Post-Amp.		EL14H082	A23S*
Pitch Axis Post-Amp.		EL15X067	Z37
Outer Roll Axis Post-Amp.		EL12A086	V13#
Azimuth Axis Demod.		EL17X071	c41
Inner Roll Axis Demod.		EL14Z059-1	Z40
Pitch Axis Demod.		EL14G080	A23
Outer Roll Axis Demod.		EL12A087	V12#

*Signal is on shield of coax.

#OR signal lines not connected at IPl

Table A-1c. IMU #3 SIGNAL LIST.

SIGNAL		PATCH BOARD POINT	
Excitation Amplifier	+15.2 VDC	EL14B052	Y42
" "	-15.2 VDC	EL14B050	Y41
Platform Voltage	+16 VDC	EL14A049	Y39
" "	-16 VDC	EL14A047	Y38
" "	+15 VDC	EL18A020	X37
" "	-15 VDC	EL18A018	X38
" "	+ 5 VDC	EL13H093	U09
Platform DC Low		EL13F103	T13
AC Power Test Point 5VAC PHIX		EL26X104	T41
AC Power Test Point 5VAC Neutral		EL27X111	T40
Clock Monitor 19.2 KHz		EL14D074	P12
Gyro Wheel Supply 0^{o} 480 Hz Sq. Wave		EL23X075	S44
Gyro Wheel Supply 90^{o} 480 Hz Sq. Wave		EL24X077	T44
X Accelerometer Coarse Level		EL22X040	Y36
Y Accelerometer Coarse Level		EL21X010	Y35
Z Accelerometer BITE		EL14C072-R	A19
X Gyro Analog Torquer Input		EL13J094	U10
Y Gyro Analog Torquer Input		EL13M097	U13
Azimuth Axis Post-Amp.		EL11X031	V36
Inner Roll Axis Post-Amp.		EL13G092	U08
Pitch Axis Post-Amp.		EL13L096	U12
Outer Roll Axis Post-Amp.		EL14E076	P11#
Azimuth Axis Demod.		EL19X064	V38
Inner Roll Axis Demod.		EL13K095	U11
Pitch Axis Demod.		EL13E102	T12
Outer Roll Axis Demod.		EL14F078-R	A22#

#OR signal lines not connected at IP1.

Table A-2. Patch Panel Signal List.

SIGNAL	IMU	PATCH PANEL POINT
Azimuth Axis Demod.	2	c41
Z Accelerometer BITE	3	A19
Outer Roll Axis Demod.	3	A22
Pitch Axis Demod.	2	A23
Inner Roll Axis Post Amp.	2	A23S
5 VAC PHI X	1	N40
5 VAC Return	1	N41
Platform +16VDC	1	N43
Platform -16VDC	1	N44
X Gyro Analog torque	1	P10
Outer Roll Axis Post Amp.	3	P11
Clock Monitor 19-2KHz	3	P12
Y Accelerometer Coarse Level	2	P31
Excitation Amplifier -15.2 VDC	2	P33
Excitation Amplifier +15.2 VDC	2	P34
Platform -16 VDC	2	P36
Platform +16 VDC	2	P37
Platform DC Low	2	P39
Platform +5 VDC	2	P40
Platform -15 VDC	1	P42
Platform +15 VDC	1	P43
X Accelerometer Coarse Level	2	Q31
GWS 0^{o}	1	Q33
GWS 90^{o}	1	Q34
Platform +5 VDC	1	Q36
Platform DC Low	1	Q37
X Accelerometer Coarse Level	1	S 40
Y Accelerometer Coarse Level	1	S 41
GWS 0^{o}	3	S44
Outer Roll Axis Demod	1	T08
Outer Roll Axis Post Amp.	1	T09
Z Accelerometer BITE	2	T10
Clock Monitor 19.2 Khz	2	T11

C-2

Table A-2. Patch Panel Signal List, continued.

SIGNAL	IMU	PATCH PANEL POINT
Pitch Axis Demod.	3	T12
Platform DC Low	3	T13
Cable Monitor	3	T35
Cable Monitor	3	T37
5 VAC Return	3	T40
5 VAC PHI X	3	T41
GWS 90°	3	T44
Inner Roll Axis Post Amp.	3	U08
Platform +5VDC	3	U09
X Gyro Analog Torque	3	U10
Inner Roll Axis Demod	3	U11
Pitch Axis Post Amp.	3	U12
Y Gyro Analog Torque	3	U13
Cable Monitor	2	U38
Cable Monitor	2	U39
Azimuth Axis Demod	1	V08
Inner Roll Axis Demod	1	V09
Pitch Axis Demod	1	V10
Z Accelerometer BITE	1	V11
Outer Roll Axis Demod	2	V12
Outer Roll Axis Post-Amp	2	V13
Inner Roll Axis Post-Amp	1	V31
Pitch Axis Post-Amp	1	V32
Azimuth Axis Post-Amp	2	V34
Azimuth Axis Post-Amp	1	V35
Azimuth Axis Post-Amp	3	V36
Clock Monitor 19.2 KHz	1	V37
Azimuth Axis Demod.	3	V38
Y Gyro Analog Torque	1	W33
Platform +15 VDC	2	W36
Platform -15 VDC	2	W37
GWS 0°	2	W39
GWS 90°	2	W40

Table A-2. Patch Panel Signal List, continued.

SIGNAL	IMU	PATCH PANEL POINT
5 VAC PHI X	2	W42
5 VAC Return	2	W43
Platform +15VDC	3	X37
Platform -15 VDC	3	X38
Excitation Amplifier -15. 2 VDC	1	X40
Excitation Amplifier +15. 2 VDC	1	X41
Cable Monitor	1	X43
Cable Monitor	1	X44
Y Accelerometer Coarse Level	3	Y35
X Accelerometer Coarse Level	3	Y36
Platform -16VDC	3	Y38
Platform +16 VDC	3	Y39
Excitation Amplifier -15. 2 VDC	3	Y41
Excitation Amplifier +15. 2 VDC	3	Y42
Y Gyro Analog Torque	2	Z33
Pitch Axis Post-Amp	2	Z37
Inner Roll Axis Demod	2	Z40
X Gyro Analog Torque	2	Z41

Table A-3. Suggested Scan Order.

FROM	TO	FUNCTION	ACCEPTABLE RANGE
T37	T35	Resistance	$< 5 \Omega$
U38	U39	"	$< 5 \Omega$
X44	X43	"	$< 5 \Omega$
N43	Q37	DC Voltage	16.0 ± 0.95 VDC
X41	Q37	"	15.2 ± 0.15 VDC
P43	Q37	"	15.0 ± 0.05 VDC
P37	P39	"	16.0 ± 0.95 VDC
P34	P39	"	15.2 ± 0.15 VDC
W36	P39		15.0 ± 0.05 VDC
Y39	T13	"	16.0 ± 0.95 VDC
Y42	T13	"	15.2 ± 0.15 VDC
X37	T13	"	15.0 ± 0.05 VDC
Y38	T13	"	-16.0 ± 0.95 VDC
Y41	T13	"	-15.2 ± 0.15 VDC
X38	T13	"	-15.0 ± 0.05 VDC
P36	P39	"	-16.0 ± 0.95 VDC
P33	P39	"	-15.2 ± 0.15 VDC
W37	P39	"	-15.0 ± 0.05 VDC
N44	Q37	"	-16.0 ± 0.95 VDC
X40	Q37	"	-15.2 ± 0.15 VDC
P42	Q37	"	-15.0 ± 0.05 VDC
Q36	Q37	"	5.0 ± 0.5 VDC
S40	Q37	"	Logic Level [1] VDC
S41	Q37	"	Logic Level VDC
V11	Q37	"	Logic Level VDC
P40	P39	"	5.0 + 0.05 VDC
Q31	P39	"	Logic Level VDC
P31	P39	"	Logic Level VDC
T10	P39	"	Logic Level VDC
U09	T13	"	5.0 + 0.05 VDC
Y36	T13	"	Logic Level VDC
Y35	T13	"	Logic Level VDC
A19	T13	"	Logic Level VDC

Table A-3. Suggested Scan Order, continued.

FROM	TO	FUNCTION	ACCEPTABLE RANGE
U10	T13	DC Voltage	Gyro Torque (2) VDC
U13	T13	"	Gyro torque VDC
Z41	P39	"	Gyro torque VDC
Z33	P39	"	Gyro Torque VDC
P10	Q37	"	Gyro Torque VDC
W33	Q37	"	Gyro Torque VDC
V10	Q37	"	Demod (3) VDC
V09	Q37	"	Demod VDC
V08	Q37	"	Demod VDC
T08	Q37	"	Demod VDC
c41	P39	"	Demod VDC
Z40	P39	"	Demod VDC
A23	P39	"	Demod VDC
V12	P39	"	Demod VDC
V38	T13	"	Demod VDC
U11	T13	"	Demod VDC
T12	T13	"	Demod VDC
A22	T13	"	Demod VDC
N40	N41	AC Voltage (400 Hz)	5.0 ± 0.2 VAC
W42	W43	"	5.0 ±0.2 VAC
T41	T40	"	5.0 ± 0.2 VAC
Q33	Q37	Sq. Wave Voltage (4)	32.0 ± 0.5 V
Q34	Q37	"	32.0 ± 0.5 V
W39	P39	"	32.0 ± 0.5 V
W40	P39	"	32.0 ± 0.5 V
S44	T13	"	32.0 ± 0.5 V
T44	T13	"	32.0 ± 0.5 V
V37	Q37	Frequency (5)	19.20 ± 0.02 KHz
T11	P39	"	19.20 ± 0.02 KHz
P12	T13	"	19.20 ± 0.02 KHz

Notes

(1) Logic Level: Accelerometer BITE Logic levels are characterized as 0.0 ± 0.5 VDC off, 5.0 ± 1.0 VDC on.

(2) Gyro Torque: Analog torque currents are here measured as DC voltages, characterized as 0.0 ± 0.005 VDC off, $\pm 7.0 \pm 0.2$ VDC on, the sign corresponding to the torquing sense.

(3) Demod: Signals shall be less than 0.1 VDC or 0.01 ma DC under slew commands. Levels during flip are to be determined.

(4) Wheel Supply Voltages: two 480 hz square waves, 90° apart in phasing, are used. These signals are 32.0 ± 0.5 VDC amplitude. GWS lines should also be scanned for AC ripple, which should be < 0.5 VAC, 400 Hz.

(5) Frequency measurements: The three clock monitor signals must be isolated at the patch board before frequency measurements can be made.

In addition to these signals, the test point harness also carries the post amplifier error signal from each servo loop to the patch panel. Whether these points can be sampled without disturbing the loops is uncertain.

APPENDIX B

MULTIPLE IMU SYSTEM TYPEWRITER FORMATS

Downlink typewriter formats for the Multiple IMU System are presented here. Identical word lists are sent to the HP2116B for storage and display five times/second. CRT formats utilizing these lists have been prepared for NASA/MSFC by Sperry Space Support Division.

The formats presented are: Checkout (Figure B-1), Ground Align (Figure B-2), Gyrocompass (Figure B-3), 3IMU FDINAV (Figure B-4) and 2IMU FDINAV (Figure B-5).

Table B-1. Checkout Format (24 16 bit words)

Word No.	Item Description	Item length	Item Type	Scaling	Units
1	code word = 0	H	INT		
2-4	X gimbal angles for IMU 1, 2, 3,	H	FX	B0	1/2 Revs
5-7	Y gimbal angles for IMU 1, 2, 3	H	FX	B0	1/2 Revs
8-10	Z gimbal angles for IMU 1, 2, 3	H	FX	B0	1/2 Revs
11-13	X CAPRIs for IMU 1, 2, 3	H	INT	B15	pulses
14-16	Y CAPRIs for IMU 1, 2, 3	H	INT	B15	pulses
17-19	Z CAPRIs for IMU 1, 2, 3	H	INT	B15	pulses
20-22	IMU status words for IMU 1, 2, 3 (for definition see below)	H	HEX		
23-24	Time	F	INT		centi-secs

Definition of IMU status word

bit 0 - GYPTO torquing failure
1 - Gimbal read failure
2 - IMU status word read failure
3 - CAPRI read failure
4 - IMU command write failure
5 - BITE failure
6 - Attitude FDI failure
7 - Velocity FDI failure

8 - { 0 = system Ready OFF
1 = system Ready ON

9, 10 - { 0 = IMU in Ground Align Mode
10 = IMU in Inertial/Normal Mode

11 - X-axis slewing
12 - Y-axis slewing
13 - Z-axis slewing
14 - IMU is hard failed (unrecoverable)
15 - IMU is soft failed (via FDI)

Table B-2. Ground Alignment Format (54 16 bit words).

Word No.	Item Description	Item length	Item Type	Scaling	Units
1	Code word = 1	H	INT		
2-22	Same as checkout format				
23-28	X-axis Tilts for IMU 1, 2, 3	F	FX	B-3	rad
29-34	Y-axis Tilts for IMU 1, 2, 3	F	FX	B-3	rad
35-40	Azimuth offsets for IMU 1, 2, 3	F	FX	B1	rad
41-46	X Gyro Drifts for IMU 1, 2, 3	F	FX	B-15	rad/sec
47-52	Y Gyro Drifts for IMU 1, 2, 3	F	FX	B-15	rad/sec
53-54	Time	F	INT		centi-sec

Table B-3. Gyrocompassing Format (72 16 bit words).

Word No.	Item Description	Item Length	Item Type	Scaling	Units
1	code word = 2	H	INT		
2-22	Same as checkout format				
23-28	Computed North Velocity (V_x) for IMU 1, 2, 3	F	FL		m/sec
29-34	Computed West Velocity (V_y) for IMU 1, 2, 3	F	FL		m/sec
35-40	Platform rate about X axis for IMU 1, 2, 3	F	FL		rad/sec
41-46	Platform rate about Y axis for IMU 1, 2, 3	F	FL		rad/sec
47-52	Platform rate about Z axis for IMU 1, 2, 3	F	FL		rad/sec
53-58	X Gyro Torquing rate for IMU 1, 2, 3	F	FL		rad/sec
59-64	Y Gyro torquing rate for IMU 1, 2, 3	F	FL		rad/sec
65-70	Z Gyro torquing rate for IMU 1, 2, 3	F	FL		rad/sec
71-72	Time	F	INT		centi-sec

Table B-4. 3 IMU FDI/Navigation Format (60 16 bit words).

Word No.	Item Description	Item length	Item Type	Scaling	Units
1	Code word=3	H	INT		
2-22	same as checkout format				
23-24	Latitude	F	FL		rad
25-26	Longitude	F	FL		rad
27-28	Altitude	F	FL		meters
29-30	East Velocity	F	FL		m/sec
31-32	North Velocity	F	FL		m/sec
33-34	Radial Velocity	F	FL		m/sec
35-40	Error Detection Ratios for X, Y, Z axis	F	FL		
41-46	Error Isolation Ratios for IMU 1 on X, Y, Z axes	F	FL		
47-52	Error Isolation Ratios for IMU 2 on X, Y, Z axes	F	FL		
53-58	Error Isolation Ratios for IMU 3 on X, Y, Z axes	F	FL		
59-60	Time	F	INT		centi-sec

Table B-5. 2 IMU FDI/Navigation Format (64 16 bit words).

Word No.	Item Description	Item length	Item Type	Scaling	Units
1	code word=4	H	INT		
2-34	Same as 3 IMU FDI/Navigation format				
35-36	Velocity Error Detection Value	F	FL		m/sec
37-42	Velocity Error Isolation Unit Vector for non-skewed IMU	F	FL		
43-48	Velocity Error Isolation Unit Vector for skewed IMU	F	FL		
49-50	Attitude Error Detection Value	F	FL		rad
51-56	Attidude Error Isolation Unit Vector for non-skewed IMU	F	FL		
57-62	Attitude Error Isolation Unit Vector for skewed IMU	F	FL		
63-64	Time	F	FL		centi-sec

APPENDIX C

CONVERTING "CASE" VALUES TO INTERNAL FORMATS

The 19 calibration parameters are used in real time instrument compensation by the executive during Ground Alignment, Gyrocompass, FDI and Navigation. Because of timing considerations during these modes, it is necessary to perform these compensations using fixed point arithmetic. Thus, if "case" values are to be loaded into 4π-CP2 memory, they must be converted to fixed point. The following is a table of conversion factors to be applied to the parameters. Converted parameters should be loaded into the indicated addresses using the FIX, command. Note that they are in consecutive full word locations.

Table C-1. Compensation Parameter Conversion Factors.

Parameter	"Case" Value Multiplied by	Store in Location	Comment
KHX IMU 1	2496.9266	0A80	High Gain Accelerometer Scale Factor
2	"	0A82	
3	"	0A84	
KHY IMU 1	"	0A86	
2	"	0A88	
3	2496.9266	0A8A	
BLX IMU 1	+2.4384049	0A8C	Low Gain Accelerometer Bias
2	"	0A8E	
3	"	0A90	
BLY IMU 1	-2.4384049	0A92	
2	"	0A94	
3	"	0A96	
BLZ IMU 1	+2.4384049	0A98	
2	"	0A9A	
3	"	0A9C	
BHX IMU 1	+2.4384049	0A9E	High Gain Accelerometer Bias
2	"	0AA0	
3	"	0AA2	
BHY IMU 1	-2.4384049	0AA4	
2	"	0AA6	
3	"	0AA8	
DIAX IMU 1	.15886382	0AAA	Gyro Drift due to Acceleration Along Gyro Input Axis
2	"	0AAC	
3	"	0AAE	
DIAY IMU 1	"	0AB0	
2	"	0AB2	
3	"	0AB4	
DIAZ IMU 1	"	0AB6	
2	"	0AB8	
3	.15886382	0ABA	

Table C-1 (cont).

Parameter	"Case" Value Multiplied by	Store in Location	Comment
DXRA IMU 1	+.15886382	0A38	Bias drifts
2	"	0A3A	
3	"	0A3C	
DYRA IMU 1	- .15886382	0A3E	
2	"	0A40	
3	"	0A42	
DZRA IMU 1	+.15886382	0A44	
2	"	0A46	
3	.15886382	0A48	
DUX, Y, Z etc.	0	0A4A	These locations contain thermal sensitive drift components called out in Ground Alignment, and should be made zero.
	0	0A5A	
KGX IMU 1	1.2709105	0A5C	Gyro Torquing Scale Factor
2	"	0A5E	
3	"	0A60	
KGY IMU 1	"	0A62	
2	"	0A64	
3	"	0A66	
KGZ IMU 1	"	0A68	
2	"	0A6A	
3	1.2709105	0A6C	
KLX IMU 1	19.507239	0A6E	Low gain Accelerometer Scale Factor
2	"	0A70	
3	"	0A72	
KLY IMU 1	"	0A74	
2	"	0A76	
3	"	0A78	
KLZ IMU 1	"	0A7A	
2	"	0A7C	
3	19.507239	0A7E	

APPENDIX D

SYSTEM ERROR MESSAGES AND CODES

Messages and codes generated by the multiple IMU system software are drawn from those tabulated in this Appendix. Tables D-1 through D-4 are Tape 1 messages. Table D-5 lists Tape 2 messages.

Table D-1 lists Executive messages.

Table D-2 lists TYPIO messages.

Table D-3 lists FDI messages.

Table D-4 lists Ground Alignment messages.

Table D-5 lists Calibration messages.

Table D-1. Executive Error Messages.

ERR, Ai	Gyro torquing error, IMU i
ERR, Bi	Gimbal read error, IMU i
ERR, Ci	Status word read error, IMU i
ERR, Di	CAPRI read error, IMU i
ERR, Ei	Command output error, IMU i
ERR, Fi	IMU BITE, IMU Fault or IMS Fail, IMU i where i = A implies IMU 1 i = B implies IMU 2 i = C implies IMU 3
ERR, AD	IMU sync message error
ERR, DA	HP output error
ERR, DB	HP output error present for more than one minute
ERR, ji	CAPRI hard failure, IMU i, where j = 0 implies X axis j = 1 implies Y axis j = 2 implies Z axis
ERR, ji	Gimbal rate hard failure, IMU i, where j = 5 implies Roll j = 6 implies Pitch j = 7 implies Azimuth
ABT, Fk	Major cycle program duty cycle too long, MC_k (k = 1, 2, 3, 4)
ABT, x	I/O complete interrupt not received, minor cycle x (x = 00, 01, ... 09)
ABT, DC	HP input error

Table D-2. TYPIO Error Messages.

ERR, 90	Typewriter code word input error
ERR, 91	Typewriter value range input error

Table D-3. FDI Error Messages and Codes.

Colinear Velocity FDI

Colinear velocity FDI for three IMUs has two levels of failure detection: 3σ and redline. Only when a redline failure has been detected and isolated will the failed IMU be soft failed and removed from navigation processing.

ERR, jC	3σ error detection on axis j (j = 1, 2, 3)*
ERR, iD	3σ error isolated to IMU i
ERR, jE	Redline error detection on axis j (j = 1, 2, 3,)*
ERR, iF	Redline error isolated to IMU i

Colinear Attitude FDI

ERR, jA	Attitude error detection on axis j (j = 1, 2, 3)*
ERR, iB	Attitude error isolated to IMU i

Skewed IMU FDI

ERR, 81	Velocity error detected
ERR, 82	Attitude error detected
ERR, ij	Error isolated to IMU i, axis j, where i = A implies IMU 1, B implies 2 and C implies 3 j = A implies X axis, B implies Y and C implies Z

*The axis code is: j = 1 implies X axis, 2 implies Y, and 3 implies Z.

Table D-3 (cont).

Skewing Indications

While skewing to the two skewed IMU configuration, the following printouts will be observed:

MSG, EB	IMU 2 starting to skew
MSG, EC	IMU 3 starting to skew
MSG, FB	IMU 2 skewing ended
MSG, FC	IMU 3 skewing ended

Note that in all cases, the lower number IMU is held inertially while the higher number remaining IMU is skewed. Thus, no skew messages are required for IMU 1.

Table D-4. Ground Alignment Error Messages and Codes.

MSG, x	Start of ground alignment sequence x, x = 00, 01, ... 10
ERR, 3i	X gyro autobias > 1°/hr, IMU i
ERR, 4i	Y gyro autobias > 1°/hr, IMU i

Table D-5. Calibration Error Messages (Tape 2).

MSG, 20	All calibration sequences complete
MSG, 3i	Calibration sequence started, IMU i
MSG, 4i	Calibration sequence completed, IMU i
ERR, 01	Kalman filter has failed to converge
ERR, 02	Computed parameter grossly out of tolerance
ERR, 03	Gross torquing rate test failed
ERR, 1i	BITE or system ready failure, $IMU_{(i+1)}$, i = 0, 1, 2

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